Great Lakes Climate Change Project

Research Priorities for
Assessing the Impacts of
Climate Change in the Great Lakes Basin

March 1994

NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION
NOAA
U.S. DEPARTMENT OF COMMERCE

CILER

Great Lakes Commission

The Laurentian Great Lakes
ONTARIO
CANADA
U.S.A.
MINNESOTA
LAKE SUPERIOR
Great Lakes Drainage Basin Limit
Duluth
MICHIGAN
ONTARIO
Sault Ste. Marie
WISCONSIN
Green Bay
Georgian Bay
LAKE HURON
St. Lawrence River
Kingston
LAKE MICHIGAN
Traverse City
MICHIGAN
Toronto
LAKE ONTARIO
NEW YORK
N
Muskegon
Grand Haven
Milwaukee
ONTARIO
Buffalo
Lake St. Clair
Detroit
Ann Arbor
LAKE ERIE
PENNSYLVANIA
Chicago
Toledo
Cleveland
Kilometers
0
100
200
ILLINOIS
OHIO
INDIANA
Great Lakes Drainage Basin Limit

Great Lakes Climate Change

Research Priorities for Assessing
the Impacts of Climate Change
in the Great Lakes Basin

Proceedings of the Great Lakes Climate Change Workshop conducted on December 6-8, 1993 Ypsilanti, Michigan

Edited by

Clare M. Ryan, Frank H. Quinn, and Michael J. Donahue

Sponsored by

National Oceanic and Atmospheric Administration (NOAA)
Cooperative Institute for Limnology and Ecosystems Research
Great Lakes Commission

March 1994

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1.0 WORKSHOP OVERVIEW

1.1 EXECUTIVE SUMMARY

Highlights

The Global Climate Change Workshop took place December 6-8, 1993 at the Radisson on the Lake Hotel in Ypsilanti, Michigan. The approximately 50 workshop participants included representatives from state, federal and provincial governments, planners, scientists, academics, and public interest groups. Participants were drawn together through a common interest in climate change and its effects on the Great Lakes region, and the development of appropriate management strategies.

Background

As a result of increasing concern about climate change, several studies have been initiated in the United States and Canada. Both countries have a history of cooperation on the climate change issue, and have conducted a series of bilateral symposia on the implications of climate change for a number of regions in North America. A major recommendation from the first symposium was that the U.S. and Canada develop an integrated study of the Great Lakes Basin as a regional pilot project for an international response to global climate change. This workshop is the first step in developing the United States comonent of a bilateral Great Lakes Climate Change effort.

Workshop Context

The workshop on Global Change in the Great Lakes basin was cosponsored by the National Oceanic and Atmospheric Administration's (NOAA) Great Lakes Environmental Research Laboratory (GLERL), the Cooperative Institute for Limnology and Ecosystems Research (CILER), and the Great Lakes Commission. Last year, the Administrator of NOAA charged GLERL with developing the United States component of a binational Great Lakes global climate change study.

Workshop Purpose

The objective of the workshop was to link the study with an ongoing initiative coordinated by Canada's Atmospheric Environment Service. The purpose of the workshop was threefold:

- Assess the current status of global change research and impact assessment in the Great Lakes.

- Identify unmet needs in these areas.

- Develop a United States Great Lakes Climate Change Research Plan to address these unmet needs and lay the foundation for basin-wide adaptive strategies.

Workshop Structure

The workshop included nine formal presentations and five break-out discussion groups. These breakout groups were identified to discuss the paper presentations, focusing on issues related to:

1. Economic/Social Assessment and Impacts
2. Ecosystem and Public Health
3. Landscape/Long Term Measurements
4. Physical/Climate Systems
5. Water Policy and Management

The charge to each breakout group was to produce a group report to include the following tasks:

1. Statement of critical issues and needs for the issue area.
2. Set of clear research objectives for the issue area.
3. Set of critical research/monitoring/synthesis components for the issue area.
4. Definition of research management issues.
5. Identification of products to be developed and users of the products.

Paper Presentations

Nine papers were presented on the first day of the workshop.

Barry Rubin of Indiana University noted that the discussion of Global climate change has not yet addressed what global climate change will mean for individuals in specific terms of job losses or gains, wage and income effects, unemployment impacts, or population change. The lack of research identifying a variety of economic impacts is compounded by the geographic level of most analyses. Climate change research has been conducted primarily at the global level. However, neither the impacts of climate change nor climate change itself will be geographically uniform--both will be region-specific--implying that economic impacts must be addressed from a regional perspective. Only by assessing the impacts must be addressed from a regional perspective. Only by assessing the combined ecologic, economic, and human effects of global climate change in a framework that incorporates the ability of ecological systems to adapt, can various prevention and mitigation alternatives be examined and compared effectively.

Peter Timmerman of the University of Toronto pointed out that the social dynamics of climate change continue to represent the most intractable area of the climate change issue. Social impacts research has, over the past 20 years, focused mainly in three areas: 1) uncertainty concerning location, scale, onset, and duration of the pysical events; 2) uncertainty involving "first order" social interfaces with climate systems and "second order" responses to first order impacts; and 3) uncertainty involving overall social system response to impending climate change. Timmerman argues that in the climate change issue, we must now explore the implications of other factors....focus on uncertainty over questions of personal, social, and political meaning, and uncertainty involving "strategic climate" in the face of climate change, as these factors are the most important areas of social and political concern in the long run.

Joseph Koonce and Benjamin Hobbs of Case Western Reserve University reviewed the status of ecosystem health of the Great Lakes and proposed elements of a research program to understand its relation to potential climate change. Application of the notion of ecosystem health to restoration of physical, chemical, and biological integrity of the Great Lakes relies upon an analogy to human health. Unlike assessment of human health, definition of wellness is more arbitrary and includes value judgements about competing uses of the resources of the Great Lakes. They argue that there are several habitat and biological issues that overlap concerns of water quality managers, fish managers, and climate change researchers. By addressing these issues in common, some of the key uncertainties, management needs, and research needs of current management will be clarified. Progress, however, will require the formulation of a new research program designed around the development of a modeling system and decision support framework that enables managers to develop flexible management policies in response to uncertainty and the trade-offs of various user interests.

Robert Gray of the University of Michigan discussed the fact that the human dimensions, in terms of causes and effects of global change, cannot be ignored. When examining the effects of global change, one encounters a complex series of interrelationships within the ecosystem. The ecosystem changes that have occurred or that are expected to occur, involve a complex set of dynamics between the following components of global change: climate alteration resulting from global warming and other factors; population increases and migration to urban areas; environmental pollution related to energy production and other factors; and threats to biodiversity of the earth's flora and fauna as natural areas are increasingly utilized by expanding human needs. The potential effects of global change on public health parameters are important issues and ones that require additional knowledge to assess their long term health effects. The paper discusses some of the major direct and indirect effects of global change on public health (such as hypothermia and exposure to ultraviolet radiation) and identifies areas where additional information is needed to fully understand the problems in order to minimize the health effects of global climate change.

Richard Baker of the University of Iowa presented a discussion of a variety of available research strategies that provide both qualitative and quantitative means of interpreting climates prior to historical time. Analysis of fossil pollen is the most widely used tool in reconstructing past vegetation and modeling continental climate. Yet problems inherent in pollen analysis have begun to limit the refinement of present research and modeling. A multidisciplinary approach is needed that will not only supply additional information for refining climate models, but also provide independent tests of current models and incorporate other environmental variables such as vegetation, soils, and hydrology. This approach involves analysis of larger plant materials, insect, mollusc, vertebrate, and other animal remains, isotopes in cave stalagmites, and changes in the hydrology of streams. Preliminary studies in Iowa and adjacent states have also added information on changes in these other elements of the environment, which should be incorporated into future models. Such studies should be expanded to include the Great Lakes area.

Thomas Croley II of NOAA's Great Lakes Environmental Research Laboratory explained how climate change impacts on the Great Lakes may be understood by considering atmospheric scenarios with hydrologic models. Scenarios are traditionally generated as general circulation model (GCM) simulations' of the earth's atmosphere. Typical scenario generating methods keep spatial and temporal variability the same in the adjusted data sets as in the historical base period. Changes are made independently to each historical meteorological variable, ignoring their interdependencies. GCM simulations are over grids that are coarse compared to the scale of interest in the Great Lakes. Recently, scenarios were taken from other climates and transposed to the Great Lakes to preserve reasonable spatial and temporal variations and to avoid other problems. In all methods, the linkage between the atmospheric scenarios and the hydrology models allows no feedback between the surface and the atmosphere in scenario development and hydrologic impact estimation. We must link atmospheric models to existing large-scale irregular-area surface models to adequately portray the hydrology and lake thermodynamics of the Great Lakes. Only as sufficiently fine grids become available for surface hydrology models in the next few years will hydrological impacts be directly estimable from purely gridded models.

Nagaraja Harshadeep of Harvard University outlined the issues involved in the estimation of the hydrological impacts of climate change, including issues of uncertainty in water resource planning, the difficult situation faced by water resource decision makers who may not be able to change the way they operate even if climate changes were almost exactly predicted. The paper looks at statistical comparisons of climate change predicted by different models and illustrates the use of groundtruth as a baseline for the comparisons. The results of GLERL model runs for different GCM predictions to estimate hydrologic variables in the Great Lakes basin are discussed. Finally, an outline of the research issues to be considered before the hydrologic and hence socio-economic impacts can be determined under a changed climate is presented for discussion.

Michael Donahue of the Great Lakes Commission introduced selected hydrologic and socio-economic characteristics of the Great Lakes to highlight the public policy significance of the resource generally, and the climate change issue in particular. Findings and projections from general circulation models were presented to illustrate both the direction and magnitude of projected change under various climate change scenarios. Several use sectors/characteristics of the resource provide case studies for an examination of projected impacts, socio-economic consequenses, and policy responses. Recommendations for action by regional leaders were presented, including policy elements for inclusion in a formal, federally-initiated Great Lakes climate change program.

Hadi Dowlatabadi of Carnegie Mellon University provided an overview of integrated assessment with a special focus on policy motivated integrated assessments of climate change. A taxonomy of models, as well as a discussion of the integrated assessment project at Carnegie Mellon was presented. The goal is to inform the policy making process and address research prioritization. Much of the discussion focuses on the interplay of uncertainty and the design of integrated assessment models. The paper concludes with a glimpse at the challenges ahead in the science which provides the foundation for integrated assessments, the integrated assessment methodologies, and our ability to produce useful information for policy decision makers.

Workshop Recommendations

- The potential effects of climate change and variability could have severe consequences for the economic, environmental and social fabric of the Great Lakes basin.

- It is recommended that a study be undertaken to examine the potential impacts and investigate a variety of adaptive and mitigative strategies to address the potential consequences of climate change.

- The Great Lakes basin is a valuable resource that is shared between Canada and the United States; Binational coordination efforts should continue.

- The Proceedings from the workshop shall be used as the basis for a United States plan of study, sponsored by NOAA.

1.2 WORKSHOP AGENDA

Global Climate Change Workshop

December 6-8, 1993
Ypsilanti, Michigan

Agenda

Monday, December 6 **12:00 p.m.- 5:00 p.m.**

Registration 11:30 a.m.- 12:00p.m.

Welcome, Opening Remarks: 12:00 p.m.
Frank H. Quinn, GLERL
Russell Moll, CILER
Michael Donahue, Great Lakes Commission

Canadian Perspective: 12:30 p.m.
Linda Mortsch, AES

Issue Paper Presentations: 1:00 - 5:00 p.m.

Issue Area		Presenter
Economic Assessment and Impacts	(1:00-1:20)	Barry Rubin, Indiana University
Social Assessment and Impacts	(1:20-1:40)	Peter Timmerman, University of Toronto
Ecosystem Health	(1:40 - 2:00)	Joe Koonce, Case Western Reserve University
Landscape	(2:00 - 2:20)	Richard Baker, University of Iowa
Physical/Climate Systems	(2:20 - 2:40)	Tom Croley, GLERL
Break	**2:40 - 3:00 p.m.**	

Public Health	(3:00 - 3:20)	Robert Gray, University of Michigan
System Integration/Data Management	(3:20 - 3:40)	Hadi Dowlatabadi, Carnegie Mellon Univ.
Water Policy and Management	(3:40 - 4:00)	Nagaraja Harshadeep, Harvard University
	(4:00 - 4:20)	Michael Donahue, Great Lakes Commission

Tuesday, December 7 **8:30 a.m.- 5:00 p.m.**

Issue Area Breakout Groups 8:30 a.m. - 12:00 p.m.

Charge to Breakout Group participants: Produce a group report to include the following tasks:

1. Statement of critical issues and needs for the issue area.
2. Set of clear research objectives for the issue area.
3. Set of critical research/monitoring/synthesis components for the issue area.
4. Definition of research management issues.
5. Identification of products to be developed and users of the products.

Breakout Groups	Chair	Room
Economic/Social Assessment and Impacts	John Kangas	Conf A
Ecosystem and Public Health	John Gannon	Seminar 1
Landscape/Long-Term Measurements	Richard Bartz	Seminar 2
Physical/Climate Systems	In Young Lee	Seminar 4
Water Policy and Management	Tom Crane	Seminar 5

Break	**10:00 a.m.-10:15 a.m.**
Lunch	**12:00 - 1:00 p.m.**
Breakout Groups Present Preliminary Reports	1:00 p.m. - 2:30 p.m.
Break	**2:30 p.m. - 2:45 p.m.**
Discussion of Preliminary Reports	2:45 p.m. - 4:00 p.m.
Breakout Groups Reconvene	4:00 p.m. - 5:00 p.m.
Wednesday, December 8	**8:30 a.m.- 12:00 p.m.**
Plenary Session: Breakout Groups Present Final Reports	8:30 a.m. - 10:00 a.m.
Discussion	10:00a.m. - 12:00 p.m.
Wrap Up, Adjourn	**12:00 p.m.**

2.0 ECONOMIC/SOCIAL ASSESSMENT AND IMPACTS

2.1 ISSUE PAPERS

Economic Impacts of Global Climate Change on the Great Lakes Region

by
Barry M. Rubin
School of Public and Environmental Affairs
Indiana University

Introduction

Global climate change has been widely discussed in the academic literature and the popular press. Yet beyond sweeping generalizations or lists of possible effects, this discussion has not addressed what global climate change will mean for individuals in specific terms of job losses or gains, wage and income effects, unemployment impacts, or population change. A report prepared by the Committee on Earth and Environmental Sciences as a supplement to the President's Fiscal Year 1992 budget highlights this problem by stating that current global climate analyses "...have been hampered by a lack of fundamental economic research on resource- economy-environmental interactions" (17). The report identifies the following critical research priorities:

- to document economic system and sector trends that determine economic inputs and sensitivities to global change;
- to focus studies on economic issues surrounding inputs, consequences, and responses to global change, and;
- to develop interdisciplinary linkages to address issues that cross-cut the natural and economic sciences.

The lack of research identifying such economic impacts is compounded by the geographic level of most analyses. Climate change research has been conducted primarily at the global level. However, neither the impacts of climate change nor climate change itself will be geographically uniform -- both will be region-specific -- implying that economic impacts must be addressed from a regional perspective.

This regional approach is even more critical to identifying and evaluating various strategies for prevention or mitigation of the effects of climate change. Given the spatial dimensions of climatological effects and ecological systems, prevention and adaptation strategies will have considerable regional variation, so that a regional perspective is necessary to provide an accurate assessment of the economic consequences of specific strategies. Only by assessing the combined ecologic, economic, and human effects of global climate change in a framework that incorporates the ability of ecological and economic systems to adapt, can various prevention and mitigation alternatives be examined and compared effectively.

Global Climate Change

In 1827, the French mathematician Baron Jean-Baptiste- Joseph Fourier first predicted a probable increase of 4 to 6 °C in the Earth's temperature subsequent to a doubling of carbon dioxide released from burning fossil fuels (22). In 1896, the Swedish chemist, Svante Arrhenius, made the first forecast of global warming based upon increasing concentrations of atmospheric carbon dioxide (1). The greenhouse effect is now one of the most well-established theories in atmospheric science. Yet the threat of the greenhouse effect and global warming received little attention until 1957, when it was reported that the oceans were not absorbing carbon dioxide at a previously assumed rate (43).

Since then, an astounding level of research has been conducted on the climatic effects of the accelerated generation of greenhouse gases. As a result, it is believed that climate changes impact biological diversity, wildlife and habitat fragmentation, species extinction, hydrology and water resources, agriculture and food resources, fishing and fisheries, human health, transportation, energy consumption and demand, and insurance costs. The concern over global climate change has stimulated and accelerated research and development efforts aimed at forecasting climate trends. Predicting global climate change has been largely rooted in the use of general circulation models (GCM) based on numerical simulation methods, as well as various reconstructions of past climates (5, 11, 36).

GCMs, however, were not designed for climatic analysis; they are relatively young so that their predictions are difficult to place within confidence limits; they are difficult to build, maintain, and use (44); and, they are limited by computer resources (26). Despite these limitations, Robinson suggests that GCM results can be used to "establish background scenarios for economic, demographic, and resource trends that are to be anticipated concurrently with possible climatic change over the next 2-12 decades" (44).

There has been some regional research utilizing GCMs. Comparisons of the different models' projections for specific resource regions include the potential effects of climate change on soil moisture (24, 32); regional GCM temperature and precipitation simulations (21, 47); and the potential effects of climate change on water resources of the Great Lakes basin (13,14,15,18). One of the most comprehensive studies utilizing GCMs for regional analysis was prepared by Smith and Tirpak for the Office of Research and Development of the U.S. Environmental Protection Agency (EPA) in 1990, and focused on the Great Lakes (49). The results of this study are described in the next section.

Economic Impacts of Climate Change and the Great Lakes Economy

No agreement exists about the full nature and magnitude of the economic effects of global warming. Nordhaus (38, 39) predicts that 3% of U.S. national income is sensitive to climate change, and that global warming will lead to a 0.25% decrease in GNP, or a loss of approximately $14 billion per year. Cline (12), however, predicts a $61.6 billion per year decrease in national income for a 2.5 degree Celsius rise in temperature, and a decrease of $335.7 billion per year if temperature rises 10 degrees Celsius. Although the major impacts of global climate change are not predicted to occur until well into the next century, rare "weather events," such as blizzards and severe droughts, are becoming more common. This increased frequency of weather events is believed to be correlated with temperature increases which may be a result of global warming. The average global cost of these events is estimated at $40 billion per year (30). The drought of 1988 alone cost the United States an estimated $39 billion (10); the heavy snow of 1982 accounted for $6 billion in direct losses (27); the severe winter of 1976-77 cost the U.S. $40 billion in production, transportation, retail sales, and energy consumption losses; and the 1980 heat wave/drought cost another $15-20 billion. Such weather events affect not only the GNP, but also impact migration patterns, the mix of business activity in a region, and the adaptation of new technology. The "dustbowl" drought of the 1930s illustrates how a weather event may cause large changes in each of these areas.

The U.S. portion of the Great Lakes region encompasses one tenth the U.S. land area, one fifth the population, and leads the country in key economic sectors, including agriculture and manufacturing. The region has fertile soils, abundant northern forests, moderate temperatures, plentiful rainfall, and inexpensive transportation. On the Canadian side, Ontario borders four of the five Great Lakes and is Canada's most populous and second largest province. However, the rich water resources in the Great Lakes (containing 18% of the world's and 95% of the U.S.'s fresh water), which are vital to the economic livelihood of the region, are severely threatened by global climate change and the potential redistribution of water resources.

The most recent and comprehensive study of the impacts of climate change on the Great Lakes region was prepared by Smith and Tirpak for the Office of Research and Development of the U.S. Environmental Protection Agency (EPA) in 1990 (49). Their conclusions were that "global climate change could affect the Great Lakes, by lowering lake levels, reducing the ice cover, degrading water quality in rivers and shallow areas of the lakes...expand agriculture in the north, change forest composition, decrease regional forest productivity in some areas, increase open water fish productivity, and alter energy demand and supply." In addition to Smith and Tirpak's work, empirical climate change research efforts in the Great Lakes region have been directed at lake levels (7, 9, 19, 25, 42), limnology (8, 35), ice cover (2,3), fishing and fisheries (33, 37), and economic issues.

In the Great Lakes region, global climate change would primarily impact nine economic sectors. These are agriculture and forestry, energy, construction, shipping, fisheries, recreation, manufacturing, retail/commercial trade, and the public sector. Great Lakes agricultural production is valued at almost $10 billion per year. Although no projections of the overall impact of global warming on the Great Lakes states yet exist, Cline (12) estimates annual U.S. agriculture losses at $5.9 billion, given a 2.5 degree Celsius rise in mean temperature. This problem is exacerbated by the uniformity of crop gene pools, which make them more vulnerable to weather shifts (45, 46). Global climate change will also change the composition, abundance, and values of forest biomasses. Although an increase in high latitude forest biomass is expected, especially in Canada, potential dry sites in central Michigan will decrease biomass by as much as 77-99% within 30-60 years (29). Van Kooten (50) and Singth and Higinbotham (48) predict other impacts, including more frequent and intense forest fires and increased insect activity. The results of tree species migration will also impact forest related industries and forestry management (30, 41, 50).

The benefit of global climate change to the construction industry in the Great Lakes region is a prolonged building season. The costs, due to temperature rise and increasing severe storms, are lost work days, damaged materials, and a 30-40% increase in the costs of building coastal or lakeshore homes (23). A 1° C increase in temperature above the optimal can cause a 2-4% decrease in productivity (31). Lower lake levels in the Great Lakes could mean hundreds of millions of dollars in reconstruction costs for marinas, port facilities, water supply and outfall sources, and beaches (49).

Although global climate change is expected to reduce the ice cover [thereby leaving the lakes free for navigation 11 months of the year (42)], low lake levels due to increasing consumptive water use, changing precipitation patterns, and evapotranspiration are expected to offset this benefit (28, 29, 34, 49). Mean annual costs to shipping are expected to rise 30%, with the low lake levels of the 1960s occurring as often as 77% of the time (34). Several studies predict that with increasing consumptive water use and a decreasing net basin supply, water rights conflicts will intensify (9, 13, 14, 15).

The Great Lakes fishing industry accounts for a total indirect and direct regional income estimated at $2.3-4.3 billion (52). Bakun (4) predicts that an increase in the production of fisheries will occur in areas of warm upwelling. However, analysis of historical patterns suggests that increased levels and types of invading species to the Great Lakes will continue to alter fish communities (33). Warmer lake temperatures, for example, will be more conducive to some fish species such as bass, but less supportive of species such as trout. Lower water levels or warmer water in the streams and rivers feeding the Great Lakes could reduce suitable spawning habitat of several Great Lakes species. Changes in either the quantity of fish or the mix of species would likely have important impacts on both commercial and sport fishing. A reduced flow of water into the Great Lakes could also increase water pollution levels, even with no increase in pollution discharge. Increased water pollution could, through bioaccumulation, increase pollution concentrations in Great Lakes fish, eventually diminishing their suitability for human consumption even if fish populations did not increase. In addition, such increased pollutant concentrations will reduce water quality, thereby reducing fish production (49).

These are critical climate-related issues for the Great Lakes basin and the U.S. Agricultural and manufacturing industries have the potential for adaptation/mitigation via migration to more hospitable locations. In the case of the Great Lakes fisheries, however, there is far less migration potential. While lakes in other locations may become suitable for some Great Lakes species, the Great Lakes scale offers a unique habitat for many fish species. Thus, in the Great Lakes basin, the emphasis must be on adaptation of a specific and unique resource.

A warmer climate is likely to provide a net increase to Great Lakes vacation and recreation activities. Camping, canoeing, boating, golf, hunting, and sports fishing will increase, and downhill skiing, cross-country skiing, and snowmobiling will decrease (20, 51). Tourism to the 67 state and 3 national parks along the Great Lakes U.S. shores is expected to rise, so much so that overuse may become a problem (49). Canada would likely have similar impacts. The primary direct impacts of global climate change on manufacturing and retail/wholesale trade will be through changes in energy use and other consumption patterns. The effects of weather on manufacturing industries have been studied extensively (3, 31, 40). Water resource consumption in other regions is likely to benefit the Great Lakes as high- technology companies are drawn to large sources of clean water. These companies will be competing with traditionally inefficient water use and polluting industries, such as pulp and paper and waste disposal. An effect of climate change on the public sector may be a reduction in tax base as lakeshore land values drop due to lower lake levels and increased pollutants, although these may be partly offset by in-migration from coastal regions (49). Increased demand for public expenditures for disaster relief could occur due to severe weather events, with potential increases in public sector employment.

Identifying Specific Employment, Income, and Unemployment Effects

Although the description of the potential economic impacts of global climate change contained above is illustrative of the effects that are likely to occur within the Great Lakes basin, this discussion does not detail the specific impacts on jobs, wages, income, unemployment, etc. To determine the impacts of global climate change on such traditional indicators of economic health, and to develop prevention/mitigation strategies for the Great Lakes, demands an interdisciplinary research effort to address interactions between environmental effects and their resulting economic impacts. While some interdisciplinary research of this type has been undertaken, much more is required to identify these interactions. Moreover, the interdisciplinary research that does exist is limited in scope to some specific sectors. The need for additional research to establish regional environmental-economic linkages is severe.

The most promising approach to delineating the full spectrum of economic impacts of global climate change on the Great Lakes basin is a multi-equation, econometric economic-environmental model focused primarily on the seven-state U.S. region and the Canadian province of Ontario. The inclusion of Ontario in such an analysis is critical, for this province contains much of the watershed that drains into four of the five Great Lakes, and adaptation to climate change in Ontario could have an important impact throughout the Great Lakes system.

Such a model could translate climate-change effects on temperature, precipitation, lake level, biological productivity, and ecosystem health into economic impacts. Research hypotheses concerning the interaction of climate-induced environmental and economic effects could be tested as part of the modeling framework. Moreover, the validity of the econometric modeling methodology in this context has clearly been demonstrated by the utilization of a similar modeling framework by the author to identify the economic impacts of global climate change for the Pere Marquette basin in west central Michigan.

The employment component of this model, together with an assessment of the initial employment impacts, is provided in Tables 1 through 4.

The results of the estimation process for the nine employment equations of the Pere Marquette model reveal a definite relationship between climate variation and regional employment. These linkages between climate and regional economic activity are summarized in Table 3, which identifies the seven climate variables which are statistically significant in the equations; presents the relevant coefficients for each equation in which these variables appear; and provides the net change in the region's total employment that would result from a one unit change in each climate variable.

The regression coefficients presented in Table 3 can be further utilized to derive employment impacts under various global climate change scenarios. A forecast of a 3.94 degree C increase in surface air temperature and a 10.1 % increase in precipitation as a result of global climate change has been derived for the Great Lakes region by Karl, *et al.* (53). This climate change scenario assumes a doubling of CO_2 in the atmosphere, and was generated by averaging the projections of five General Circulation Models. For the Pere Marquette region, the average ratio between mean temperature and precipitation levels in the study area and peak and mean summer and winter levels were used to derive projections of these latter variables. Table 4 displays the potential employment impacts of this climate change scenario for the four-county study area.

At first glance, the employment impact estimates in Table 4 would seem to indicate that the consequences of climate change on the region would be minimal -- a net loss of 94 jobs. But a more detailed examination of Table 4 reveals that the net employment change obscures substantial sectoral impacts. The analysis projects a loss of 818 jobs in manufacturing and 169 jobs in transportation/public utilities, and a gain of 1,049 jobs in the services sector. Such a substitution of low-paying services employment for the higher-paying jobs in manufacturing and transportation/utilities exacerbates existing trends in this direction. The sensitivity of each sector to the specific elements of climate change -- variation in mean temperature, peak temperature, precipitation level, etc. -- can also be evaluated.

It is precisely this type of modeling framework which is required to determine the specific economic impacts of global climate change on the Great Lakes region. Not only can these impacts be estimated, but such a modeling structure can be used to help derive public policy that can mitigate the negative effects which will surely arise.

Table 1. Employment Equations for the Pere Marquette Global Climate Change Impact Model

1. Farming

RE_FARM = 4413.151 - 44.427 RWFARM - 1.325 NI_FOOD + 0.228 L_EFARM - 28.780 AVG_DTMP
(6.891) (-7.130) (-2.065) (1.902) (-3.443)

R-SQUARE = 0.9603 DW = 2.578 N = 21

2. Construction

RE_CONST = - 1499.426 + 0.0462 RE_TOTAL + 2471696 RLWGCON + 0.470 GNP82
(-11.820) (4.341) (23.765) (6.765)

- 31.641 RWCON
(-6.288)

R-SQUARE = 0.9851 DW = 2.350 N = 22

3. Manufacturing

RE_MFG = 38212.160 - 146.627 RWMFG + 1.945 GNP82 + 12943255 RLWGMFG - 29.833 WIN_DTMP
(2.852) (-8.253) (7.908) (6.720) (-2.309)

- 71.703 SUM_DTMP
(-3.479)

R-SQUARE = 0.9410 DW = 1.919 N = 22

4. Finance, Insurance and Real Estate

RE_FIRE = - 681.516 + 0.368 RE_TR_UT + 0.116 R_PCI + 0.010 R_POP
(-1.721) (2.593) (19.333) (2.594)

R-SQUARE = 0.9881 DW = 1.366 N = 22

5. Services

RE_SERV = - 2909.958 + 0.229 RE_MFG + 0.417 RE_CONST + 0.294 R_PCI + 77.746 AVG_DTMP
(-2.558) (3.753) (3.251) (36.109) (3.679)

+ 141.274 WIN_DPCP
(2.701)

R-SQUARE = 0.9909 DW = 2.002 N = 22

6. Wholesale and Retail Trade

RE_TRADE = - 20.227 + 0.00037 PK_ATTND + 0.418 L_RETRD + 0.125 RE_TOTAL
(-0.058) (2.539) (3.941) (5.872)

- 21.268 MPW_DTMP
(-3.031)

R-SQUARE = 0.9802 DW = 1.867 N = 21

7. State and Local Government

RE_STLOC = - 239.357 + 0.655 L_RESGV + 0.114 RE_SERV + 0.0636 NUM_PUP
(-0.336) (5.211) (3.270) (2.158)

R-SQUARE = 0.8860 DW = 1.661 N= 21

8. Transportation and Utilities

RE_TR_UT = - 1335.085 + 4129241 RLWGTPU + 0.195 GNP82 - 49.688 WIN_DPCP
(-3.188) (10.140) (4.439) (-3.077)

+ 0.000081 PROD_VAL + 0.275 RE_FARM
(4.357) (3.766)

R-SQUARE = 0.9078 DW = 2.006 N = 22

9. Residual

RE_RESID = - 2898.601 + 0.00021 NE_FGOVT + 0.090 RE_TOTAL + 57.078 WIN_DPCP
(-7.373) (3.475) (15.469) (1.827)

R-SQUARE = 0.9235 DW = 2.333 N = 22

Table 2. Employment Equation Variable Definitions for the Pere Marquette Global Climate Change Impact Model

Employment Variables:

RE_TOTAL =	Regional Total
RE_CONST =	Regional Construction
RE_FARM =	Regional Farming
L_EFARM =	Lagged (1 year) Regional Farming
RE_FIRE =	Regional Finance, Insurance, and Real Estate
RE_MFG =	Regional Manufacturing
RE_SERV =	Regional Services
RE_STLOC =	State and Local Government
L_RESGV =	Lagged (1 year) State and Local Government
RE_TRADE =	Regional Trade (Retail + Wholesale)
L_RETRD =	Lagged (1 year) Regional Trade (Retail + Wholesale)
RE_TR_UT =	Regional Transportation and Utilities

Wage Variables:

RWFARM =	Regional Wage Rate for Farming
RWMFG =	Regional Wage Rate for Manufacturing
RLWGCON =	Relative Wages for Construction
RLWGMFG =	Relative Wages for Manufacturing
RLWGTPU =	Relative Wages for Transportation and Utilities

Other Variables:

GNP82 =	Gross National Product (1982 Dollars)
NI_FOOD =	National Consumer Price Index for Food
R_PCI =	National Per Capita Income
R_POP =	Regional Population
PK_ATTND =	State Park Attendance
NUM_PUP =	Number of Pupils in Public Schools
PROD_VAL =	Value of Farming Production

Climate Variables:

SUM_DTMP =	Mean (Monthly) Summer Temperature
WIN_DTMP =	Mean (Monthly) Winter Temperature
AVG_DTMP =	Mean (Monthly) Annual Temperature
MPW_DTMP =	Mean (Monthly) Winter Peak Temperature
WIN_DPCP =	Total Winter Precipitation

Table 3. Climate Dependent Coefficients for Pere Marquette Watershed Region

Employment Sector / Climate Variable	Mean Summer Temp.	Mean Winter Temp.	Mean Peak Winter Temp.	Mean Annual Temp.	Mean Winter Precip.	Net Impact
Farming				-28.78		**-28.78**
Manufacturing	-71.70	-29.83				**- 101.53**
Services				77.75	141.27	**219.02**
Trade			-21.27			**- 21.27**
Transportation and Public Utilities					-49.69	**- 49.69**
Residual					57.08	**57.08**
Net Change	**-71.70**	**-29.83**	**- 21.27**	**48.97**	**148.66**	**74.83**

Table 4. Pere Marquette Watershed Region Employment Impacts Under Doubled CO_2 Scenario

Employment Sector / Climate Variable	Mean Summer Temp.	Mean Winter Temp.	Mean Peak Winter Temp.	Mean Annual Temp.	Mean Winter Precip.	Net Impact
Farming				-204.11		**-204.11**
Manufacturing	-676.30	-141.74				**- 818.04**
Services				551.40	497.85	**1,049.25**
Trade			-146.32			**- 146.32**
Transportation and Public Utilities					-168.68	**- 168.68**
Residual					193.89	**193.89**
Net Change	**-676.30**	**-141.74**	**- 146.32**	**347.29**	**523.06**	**-94.01**

References

(1) Arrhenius, Svante (1896). On the Influence of Carbonic Acid in the Air Upon the Temperature of the Ground. *London, Edinburgh, and Dublin Philosophical Magazine and Journal of Science*, 237-76.
(2) Assel, Raymond A. (1990). An Ice-cover Climatology for Lake Erie and Lake Superior for the Winter Seasons 1897-1898 to 1982-1983. *International Journal of Climatology*, 10:731-748.
(3) Assel, Raymond A. (1991). Implications of CO_2 Global Warming on Great Lakes Ice Cover. *Climatic Change*, 18:377-395.
(4) Bakun, A. (1990). Global Climate Change and Intensification of Coastal Ocean Up-Welling. *Science*, 247:198-201.
(5) Barnola, J. M., Raynaud, D., Korotkevitch, Y. S. and Lorius, C. (1987). Vostok Ice Core: A 160,000 Year Record of Atmospheric CO_2. *Nature*, 329:408-414.
(6) Bickert, C. Von E. and Browne, T. D. (1966). Perception of the Effect of Weather on Manufacturing: A Study of Five Firms. In W. R. D. Sewell (Ed.), *Human Dimensions of Weather Modification*, Research Paper No. 105, Department of Geography, University of Chicago, 307-322.
(7) Bishop, Craig T. (1990). Historical Variation of Water Levels in Lakes Erie and Michigan-Huron. *Journal of Great Lakes Research*, 16(3):406-425.
(8) Boyce, F. M., Schertzer, W. M., Hamblin, P. F. and Murthy, C. R. (1991). Physical Behaviour of Lake Ontario with Reference to Contaminant Pathways and Climate Change. *Canadian Journal of Fisheries and Aquatic Science*, 48:1517-1528.
(9) Bruce, James P. (1984). Great Lakes Levels and Flows: Past and Future. *Journal of Great Lakes Research*, 10(1):126-134.
(10) Changnon, Stanley and Changnon, Joyce M. (1990). Use of Climatological Data in Weather Insurance. *American Meteorological Society*, 3:568-576.
(11) Chappelaz, J., Barnola, J. M., Raynaud, D. Korotkevitch, Y. S. and Lorius, C. (1990). Ice-Core Record of Atmospheric Methane Over the Past 160,000 Years. *Nature*, 345:127-131.
(12) Cline, William R. (1992). Global Warming: The Economic Stakes. Institute for International Economics: Washington, D.C.
(13) Cohen, Stewart J. (1986a). Climatic Change, Population Growth, and Their effects on Great Lakes Water Supplies. *The Professional Geographer*, 38:317-323.
(14) Cohen, Stewart J. (1986b). Impacts of CO_2 Induced Climatic Change on Water Resources in the Great Lakes basin. *Climatic Change*, 8:135-153.
(15) Cohen, Stewart J. (1987). Sensitivity of Water Resources in the Great Lakes Region to Changes in Temperature, Precipitation, Humidity, and Wind Speed. In S. I. Solomon, M. Beran, and W. Hogg (Eds.), *The Influence of Climate Change and Climatic Variability on the Hydrologic Regime and Water Resources*, Publication No. 168, Wallingford, Berkshire, UK: International Association of Hydrology Sciences, Pub. No. 168, 489-500.
(16) Cohen, Stewart J. (1988). Great Lakes Levels and Climate Change: Impacts, Responses, and Futures. *Societal Responses to Regional Climate Change: Forecasting by Analogy*, Westview Press: Boulder, 143-167.
(17) Committee on Earth and Environmental Sciences (1991). Our Changing Planet: The FY 1992 U.S. Global Change Research Program. U.S. Geological Survey: Reston, VA.
(18) Croley II, Thomas E. (1990). Laurentian Great Lakes Double CO_2 Climate Change Hydrological Impacts. *Climatic Change*, 17:27-47.
(19) Croley II, Thomas E., M. ASCE and Hartmann, Holly C. (1989). Climate Change Effects on

Great Lakes Levels. Reprinted from *Hydraulic Engineering '89 Proceedings National Conference On Hydraulic Engineering* held 14-18 August 1989, New Orleans, LA, 653-658.
(20) Crowe, R. B. (1985). Effect of Carbon Dioxide Warming Scenarios on Total Winter Snowfall and Length of Winter Snow Season in Southern Ontario. Atmospheric Environment Services, Environment Canada: Windsor (Unpublished Manuscript).
(21) Cushman, Robert M. and Spring, Penny N. (1989). Differences Among Model Simulations of Climate Change on the Scale of Resource Regions. *Environmental Management*, 13(6):789-795.
(22) Fourier, Baron Jean-Baptiste-Joseph (1824). Les Temperatures du Globe Terrestre et des Espaces Planetaires. *Memories de L'Academe Royal des Sciences de L'Institut de France*, 7:569-604.
(23) Gilbert, Evelyn (1990). Global Warming May Boost Storm Losses. *National Underwriter: Property And Casualty/Risk & Benefits Management*, 23 Apr:6.
(24) Gleick, P. H. (1987). Regional Hydrologic Consequences of Increases in Atmospheric CO_2 and Other Trace Gases. *Climatic Change*, 10:137-161.
(25) Hartmann, Holly C. (1990). Climate Change Impacts on Laurentian Great Lakes Levels. *Climate Change*, 17:49-67.
(26) Hengeveld, Henry (1991). Understanding Atmospheric Change: A Survey of the Background Science and Implications of Climate Change and Ozone Depletion. State of the Environment Report No. 91-2, Environment Canada: Ottawa, Ontario.
(27) Hughes, Patrick (1983). Weather, Climate, and The Economy. *Weatherwise*, 35:60-3.
(28) International Joint Commission (1981). Great Lakes Diversions and Consumptive Uses. International Great Lakes Diversions and Consumptive Uses Study Board, Report to the Governments of the U.S. and Canada, Washington, D.C. and Ottawa, Ontario.
(29) International Joint Commission (1985). Great Lakes Diversions and Consumptive Uses. International Joint Commission, Report to the Governments of the U.S. and Canada, Washington, D.C. and Ottawa, Ontario.
(30) Kates, Robert W., Ausubel, J. H., and Berberian, M. (Eds.) (1985). *Climate Impact Assessment*. John Wiley & Sons: New York.
(31) Kellog, William W. and Schware R. (1981). Climate Change and Society: Consequences of Increasing Atmospheric CO_2. Westview Press: Boulder.
(32) Kellogg, William W. and Zhao, Zong-Ci (1988). Sensitivity of Soil Moisture to Doubling of CO_2 in Climate Model Experiments. Part I: North America. *American Meteorological Society*, 1:348-366.
(33) Mandrak, Nicholas E. (1989). Potential Invasion of the Great Lakes by Fish Species Associated with Climatic Warming. *Journal of Great Lakes Research*, 15(2):306-316.
(34) Marchand, D., Sanderson, M., Howe, D. and Alpaugh, C. (1988). Climatic Change and Great Lakes Levels: The Impact on Shipping. *Climatic Change*, 12:107-133.
(35) McCormick, Michael J. (1990). Potential Changes in Thermal Structure and Cycle of Lake Michigan Due to Global Warming. *American Fisheries Society*, 119:183-194.
(36) McGhee, Robert (1981). Archeological Evidence for Climatic Change During the Last 5000 Years. In T. M. L. Wigley,Ingram, M. J. and Farmer G. (Eds.), Climate and History: Studies in Past Climates and Their Impact on Man, Cambridge University Press: Cambridge, 162-179.
(37) Meisner, J. Donald, Goodier, John L., Regier, Henry A., Shuter, Brian J. and Christie, W. Jack (1987). An Assessment of the Effects of Climate Warming on Great Lakes basin Fishes. *Journal of Great Lakes Research*, 13(3):340-352.
(38) Nordhaus, William D. (1991a). A Sketch Of The Economics Of The Greenhouse Effect. *Greenhouse Warming*, 81(2):146-156.

(39) Nordhaus, William D. (1991b). To Slow or Not to Slow: The Economics of the Greenhouse Effect. *The Economic Journal*, 101(6):920- 937.
(40) Palutikof, J. (1983). The Impact of Weather and Climate on Industrial Production in Great Britain. *Journal of Climatology*, 3:65- 79.
(41) Parry, M. L., Carter, T. R., and Konijn, N.T. (Eds.) (1987). The Impact of Climate Variations on Agriculture. Vol. 1, *Assessments in Cool Temperature and Cold Regions*, Reidel: Dordrecht.
(42) Potter, Kenneth W. (1992). Estimating the Probability Distribution of Annual Maximum Levels on the Great Lakes. *Journal of Great Lakes Research*, 18(1):229-235.
(43) Revell, Roger and Suess, H. E. (1957). Carbon Dioxide Exchange Between Atmosphere and Ocean and the Question of an Increase of Atmospheric CO_2 During the Past Decades. *Tellus*, 9:18-27.
(44) Robinson, Jennifer (1985). Global Modeling and Simulations. In R. W. Kates, J. H. Ausubel and M. Berberian (Eds.), *Climate Impact Assessment*, John Wiley & Sons: New York, 469-492.
(45) Rosenberg, N. J. (1986). Climate Change: A Primer. Resources for the Future, Inc., Washington, D.C.
(46) Rosenberg, N. J., Easterling, III, W. E., Crosson, P. R., and Darmstadter, J. E. (1989). Greenhouse Warming: Abatement and Adaption. Resources for the Future, Inc., Washington, D.C.
(47) Santer, B.D. and Wigley, T.M. (1990). Regional Validation of Means, Variances, and Spatial Patterns in General Circulation Model Control Runs. *Journal of Geophysical Research*, 95(D1):829-850.
(48) Singth, T. and Higginbotham, K. O. (1988). An Overview of the Effects of Climate Change and Climatic Variability on Forest Vegetation in Western Canada. In Magill, B.L., and Geddes F (Eds.), *The Impact Of Climate Variability and Change on the Canadian Prairies*, Alberta Environment: Edmonton, 255-74.
(49) Smith, Joel B. and Tirpak, Dennis A. (1989). The Potential Effects of Global Climate Change on the United States. Report to Congress, U.S. Environmental Protection Agency, Office of Policy, Planning and Evaluation.
(50) Van Kooten, G. C. (1989). Assessing Economic Benefits of Climate Change on Canada's Boreal Forest. *Canadian Journal of Forest Research*, 19:463-470.
(51) Wall, G. (1985). Climate Change and its Impact on Ontario Tourism and Recreation. Environment Canada: Windsor, Canada.
(52) Talhelm, Daniel R. (1988). Economics of Great Lakes Fisheries: A 1985 Assessment. Technical Report No. 54, Great Lakes Fishery Commission.
(53) Karl, T. R., H. Diaz, and T. Barnett. 1989. Climate Variations of the Past Century and the Greenhouse Effect. A report based on the First Climate Trends Workshop, Rockville, MD: National Climate Program Office/NOAA.

The Social Dimensions of Climate Change Research: From Impacts to Strategies

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Introduction

The social dynamics of climate change continue to represent the most intractable area of the climate change issue. This is true for a number of reasons, including (in ascending order of intractability):

1) Uncertainty concerning location, scale, onset, and, duration of the physical events;

2) Uncertainty involving "first-order" social interface with climate system (i.e. how do we know what is going to be there when the climate changes?);

3) Uncertainty involving "second-order" responses to (and cascading impacts from) "first-order" impacts;

4) Uncertainty involving overall social system response to impending climate change;

5) Uncertainty involving "strategic climate" in the face of climate change;

6) Uncertainty over questions of personal, social, and political meaning.

Roughly speaking, social impacts research has, over the past 20 years, been mostly located in areas 1, 2, and 3, with occasional forays into 4. It was only within the last five years or so that any significant work has been done in areas 4-6.

Areas 4-6 are the most important areas of social and political concern in the long run, given the brute fact that areas 2 and 3 depend a great deal on area 1, and area 1 is where the physical scientists and modellers tell us that the uncertainties are unlikely to be resolved any time soon. We therefore require a strategic context within which social responses will make sense. Therefore, I argue that in the climate change issue, we need now to explore the implications of a top-down approach, and no longer concentrate so heavily on the bottom-up approach, important as it is. In essence, we should begin with issues 4-6, and work backwards to 1-3.

From Impacts to Strategies

In a 1989 paper, I mapped out what I referred to as 3 generations of social impact research (see Figure 1). These shadow fairly straightforwardly the increasing problems of intractability, but with the main orientation being towards developing as close to a scientific cause-effect relational model as possible. There are a number of reasons for this.

To begin with, the climate issue is "front-loaded" with scientific fact, since we are dealing with a physical force, with the physical expression over time of a global physical system, and that has defined the situation since the outset. This may seem like a blindingly obvious statement to make, but it was something of a historical accident that "climate" entered into our society the way it did, as a topic of a certain kind of scientific research. If we were living in a different kind of society, climate change might have been seen as one small element of society's concern over its long term cultural or historical survival; it might have been defined as an engineering problem in our movement towards planetary restructuring, and so on.

In fact, one related reason why the generational research on climate impacts has proceeded the way it has is that, before the "first generation" of serious impacts research, climate belonged more to the province of historians, anthropologists, and geographers who made sweeping generalizations about the influence of climate on various historical epochs or tribal customs, based on anecdote and very scattered facts. So discredited was this approach, that when 1st generation "impacts research" began, there was a conscious effort to stick as closely to the "facts" as possible. Moreover, climate research itself was only just emerging from the solid advances in meteorological science. It happened that the only really useful, measurable facts for climate impacts researchers at that time were the impacts of massive climate changes and the impacts of severe climate anomalies (e.g. hailstorms over apple orchards). These allowed for the gathering of both physical data, and also dollar figures.

Useful as all this research was, it is fairly clear, 15 or so years later, that much of it led into a conceptual dead end. What it put in place was a model of social impact studies which was inappropriate to the complexity of how societies do in fact relate to climate. Without going into great detail, the 2nd generation models, which took their cue from what I call a "billiard ball" approach -- that is, they assumed (often just to get some kind of results, not out of any conviction) that society responded linearly to climate -- hence the word "impacts" -- and that one could presume a kind of first-order, second-order, and so on, response to an "initiating event."

In the late 1980's, as the result of the sudden eruption of climate change into the public consciousness, a number of countries -- including most notably the U.S. -- commissioned impact studies in order to determine the possible impacts of a climate warming. A number of these studies, while important for determining possible "ballpark" figures, were also unhappy victims of the "billiard ball" syndrome, especially in the area of assessing economic costs of climate impacts. Dollar impacts for each subject area tended to be derived by holding the rest of the economy steady ("Everything Else Remains Equal") in turn, and then summing the result to achieve some enormous, if improbable result that would get the attention of the powers that be. Shifts in the international economy, in trading patterns, in the changing mix of agriculture and industry, and so on, were often assumed away. Without going into the details, it is well known that these often very plausible economic shifts and changes are easily capable of overwhelming the standard economic calculations of potential impacts from climate variability and change.

"Scenario modeling" of impacts usually derives from the GCMs or from other working assumptions of the future climate, and works through possible scenarios. These are then in turn related to potential sectors. To provide a non-North American example, the United Kingdom Climate Change Impacts Review Group in 1991 took the "Business as Usual" scenario from the IPCC, and generated scenarios for the years 2010, 2030, and 2050, "using time-dependent results from simple transient climate models to scale the spatical patterns of equilibrium warming as derived from averaging recent GCM results" (CCIRG, 1991). They are, again, useful for indicating the potential range and interconnectedness of climate impacts, but there are serious limits to their predictive capability. Note this, taken virtually at random, from the U.K. report, on the energy sector:

> It is not possible at this stage to say how energy prices might change in response to climate change. Broadly speaking, UK energy costs are likely to decrease as a result of reduced space heating needs in the early stages of the next century. However, in the longer term, increased use of air conditioning may push costs up. Price rises in response to altered demand profiles are possible, particularly for natural gas. Changes in electricity prices are less easy to predict.

This is by no means the worst example of academic bet-hedging available in the literature, and at least the British group admits its partial helplessness.

In other jurisdictions, single scenario modeling (as in the British case) is supplemented by alternative scenarios, which gain in dynamic range what they usually lose in detail.

Two ways of capturing or finessing the larger social science issues have been the multiple case study approach (Parry et al, 1988) and "forecasting by analogy" (Glantz, 1989).

The best example of the multiple case study approach was that conducted by Parry and his colleagues through UNEP/IIASA looking at the impact of climate variations on agriculture in different regions of the world. This study enabled them to compare similarities and differences in social responses to climate, and to make certain initial generalizations about tactics and strategies with regard to risk, to focus on marginalized communities whose survival often depended on the ebb and flow of climate variation (through iterative scenarios), and to look at thresholds and non-linearities in "adjoint" systems to the system under direct impact.

"Forecasting by analogy" on the other hand attempts to locate historic or prehistoric periods when the climate was warmer (or cooler, or more variable) than now. The closer the period that can be found to the present, the fewer naive assumptions one has to make about the social system, since one has such a system available in working order. There are, of course, difficulties, but in recent years researchers have focussed on extended periods such as the Great Depression in the midwest (for regional forecasts), and on some very specific years and places. Some examples of the latter kind of work involve focussing on very warm years (such as 1988 - 1992), and on local water-level rises, local droughts, etc. These analogy studies are particularly useful in revealing local sensitivies to changes and variations in climate, and in showing how the communities involved responded or adapted to these situations. The difficulty, of course, is that reality rarely repeats itself twice.

We are now, as I have suggested, in the 3rd generation of impacts research. Out of the more sophisticated impact studies in the late 1980s and the recognition of the difficulties that prompted such approaches as "forecasting by analogy," it is now widely recognized that although standard impact studies have their uses, we are now looking for other alternatives to deal with the social response to climate change.

One signal of this, from the various impact studies, is the invocation in a number of recent studies of a variety of strategies that are -- or can be deployed -- to respond to climate change. Here is a recent chart (Table 13) (1992) by Thomas Downing on adaptive responses in agriculture. He speaks of "accommodation," "planned resiliency," "purposeful adjustment," and "crisis response." This is a combination of a number of approaches, some looking at overall strategic responses to any kind of change, and some analyzing characteristics of social systems that make them specially susceptible or resistant to impacts.

This kind of approach almost necessarily involves the introduction into the discussion of social, economic, and political policies supporting or detracting from human adjustment or adaptation to potential impacts, and therefore also introduces into the discussion various fundamental social, political, and economic theories of how societies operate. This kind of discussion is so messy, so complex, and (to be frank) so often interminable that many people have for a long time tried to avoid it. Nevertheless, as I have tried to suggest, without such an introduction, there is left in place by default a model of society which has some of the following characteristics:

(1) It is defined essentially in physical, engineering terms;
(2) Society responds inelastically to environmental changes, that is, it does not learn or adapt;
(3) There is no serious conflict between different sectors of the society;
(4) Political issues, including equity considerations, are left for later.
(5) The present is presumed to be the standard for preservation or projection.

For reasons that should be fairly obvious by now, this kind of model is not very useful in describing the real world. But how do we handle an alternative discussion?

The Shifting Strategic Climate

By far the most important shift in the period within which we are now operating is that strategic considerations have, at last, come into the foreground of concern; and that we are unavoidably involved in the kinds of discussion that so many people have for so long tried to avoid. These strategic considerations have arrived, of course, partly due to the Protocols on Ozone and on Climate Protection signed at the Rio Earth Summit, and the various national and international responses to the potential of the changing climate situation. Apart from the other impacts of these frameworks of concern, they radically alter -- or perhaps I should less optimistically say, should alter -- much of the framework within which social impact analysis is carried out.

The great problem with impacts assessment has been that it has never been able to cope fully with the most important element of social and cultural change, which is the human capacity to gather, interpret, and respond to information (natural and social information). This involves issues of meaning, interpretation, and decision-making - the lifeblood of human social interaction. There have been attempts to look at these issues quite narrowly in the impacts field through certain risk analytic approaches, some economic analysis (e.g. of public versus private information), and so on. But there has been little attempt to consider what climate or climate impacts "mean" in the context of society as a whole; just as there has been great difficulty in discussing "society" - "environment" interactions as a social process, rather than as a physical process.

Let me spell this out a bit more clearly. It was one of the working assumptions of the earlier generations of impact researchers that the climate was in some sense still for all practical purposes (except perhaps cloud-seeding) fully "outside" society, and so would "impact" on society. Thanks to the prospect of climate warming and the growing hole in the ozone layer, climate is now at least partially within the power of human beings to affect, if not control. This puts it partly "inside" -- it is a bit like suddenly finding a tiger in your dining room. More obviously, just as climate impacts used to be seen as a linear flow from climate to society, the loop from society back to climate is now connected. This brings into the foreground the fact that human society is not a passive recipient of climate change, but is an active player, whose decisions (or lack of decisions) will change the nature of the future environment.

This makes climate impacts research an active player in the social decision making process. It is not neutral now, if it ever was. It also brings into the foreground the obvious fact that people's responses to climate (or to any other change) are embedded in larger social and environmental "narratives" which make those meanings make sense. Why should people adjust or adapt to climate change? Why should we adopt energy policies that will slow, mitigate, or reverse climate change? Why should we consider redistributing information, finances, technology to 3rd World countries? What is our responsibility for the climate of future generations?

What I am suggesting is that the social response to climate change -- and the impacts -- depends fundamentally on the presence or absence of a larger strategy or overall social narrative. Many of us still work within a presumed narrative which supposes a "business as usual" scenario, pivoting (as I mentioned earlier) on certain assumptions, e.g. the present status quo is to be protected and projected into the future. But there are other possibilities.

If, for example, the global community began to act as if it were a community, and committed itself to global equity and sustainability, then there would be a fundamental reorientation of national, regional, and local narratives operating within, and keying off of, that global framework. If, for example, the United States decided to move beyond the target of meeting 1990 emissions levels by 2005, and instead vigorously pursue the additional 60% reductions in emissions that some scientists suggest are required to begin to reverse climate change, then the social response would change (Rayner, 1993), because people would be forced to consider a whole range of strategic and tactical planning issues that are currently being ignored for lack of a narrative to which everyone is committed.

Similarly, we are entering an era in which the implications of climate change, and the responses to it, are going to be deeply involved in national strategies on other issues, including global trade. We are witnessing, with the evolution of the Global Environment Facility (through the World Bank and others), with the arrival of joint implementation strategies, and with the prospect of global trade-offs in many different sectors, the beginnings of a process of global management. Possible climate impacts and their mitigation are becoming negotiating tools by both developed and developing country governments, not to mention the high-level maneuvering by various multi-national corporations.

It is not necessary to go to the global level to see the implications of considerations of meaning, or of constructing (as human beings can) a future we would like to inhabit. In a number of jurisdictions -- I single out some of the innovative work being done at Environment Canada -- 3rd generation researchers are actively involving the citizenry in planning the strategic response to a possible climate warming. This participatory approach recognizes that the "climate of research" has changed, and has inevitably become politicized.

This new "climate of research" has, as yet, few useful research tools at its disposal. Two of these, which are fairly familiar, but have not been fully utilized are "policy exercises," and what is referred to as "backcasting." Policy exercises (Brewer in Clark and Munn 1986) are an interactive tool which enables policy makers to evaluate different alternative futures (or future histories). Since they are often tied to computing capacity, the policies to which the participants commit themselves can be rich or "thick" enough to be plausible alternatives. Backcasting (Robinson, 1988) is a more general -- and in some respects more creative -- approach, which depends upon the creation of a set of alternative futures, and then working backwards, slowly constraining the range of options with which the near future, and then the present, can work.

Other techniques for involving the potentially affected communities in helping to determine their own fate are being developed. They raise profound questions about the role of the researcher, about the "scientific neutrality" of the impacts researcher, and about how we as researchers see ourselves contributing towards the largest and most important of all current narratives -- the sustaining of the biosphere for continued human flourishing.

Conclusion & General Research Recommendations

- Further support should be given to "3rd Generation" research initiatives;
  - participatory research, policy exercises, backcasting and other initiatives need to be stressed in future research programmes;
  - further attention needs to be given to the range of possible strategies, from limitation strategies all the way to adaptation;

- climate research and impact research are now inescapably strategic and tactical tools for policy makers at all levels

  - whether one approves of it or not, the data, modeling, results, research design, and scientific uncertainties of the climate issue are now being almost immediately injected into various diplomatic, political, and planning negotiations. If we are to remain true to scientific and professional standards, what does this mean? -- e.g. what is the role of climate information for public and private decision-making?

- this research must respond to the need to come up with optimal strategies for governments and citizens.

  - the society-climate loop is finally closing (and not a moment too soon), and this requires citizen involvement in the emerging management of the society-climate realm;.
  - the question of expert-citizen relations is now critical;
  - the global context within which research is being carried out is appropriate and meaningful.

SELECTED REFERENCES

Beijer Institute. 1988. Developing Policies for Responding to Climate Change. Stockholm: The Beijer Institute Report on Villach and Bellagio (1987) Workshops.

Benedict, R. L. et al. 1991. Greenhouse Warming: Negotiating a Global Regime. Washington, D.C.

Burton, I. and P. Timmerman. 1988. The Human Response to Atmospheric and Other Global Changes. Paper tabled at "The Changing Atmsophere" International Conference, June 27-30, 1988, Toronto, Ontario, Canada.

Clark, W.C. and R.E. Munn. 1986. The Sustainable Development of the Biosphere. Cambridge: University Press for the International Institute for Applied Systems Analsyis, Laxenburg, Austria.

Climate Change Impacts Review Group (CCIRG). 1991. The Potential Effects of Climate Change in the United Kingdom. London: Department of the Environment, HMSO.

Downing, T.E. 1992. Climate Change and Vulnerable Places. Oxford: Global Environmental Change Unit (Univ. of Oxford).

Glantz, M. (ed.) 1989. "Forecasting by Analogy": Societal Responses to Regional Climatic Change. Boulder, Colo.: National Center for Atmospheric Research for the USEPA.

Hare, F.K. 1981. "Understanding Climate-Society Interaction" in SCOPE Newsletter, No. 14, October 1981.

Kates, R.W., J.H. Ausubel, M. Berberian (eds.). 1985. Climate Impact Assessment. Chichester: John Wiley and Sons.

Matthews, J.T. 1987. Global Climate Change: towards a greenhouse policy. From: Issues in Science and Technology, Vol.3, No. 3.

Meyer-Abich, K. M. "Chalk on the White Wall? On the Transformation of Climatological Facts into Political Facts," in Ausubel, J. and Biswas, A.K. (eds.) Climate Constraints and Human Activities. Oxford: Pergamon Press, pp. 61-94.

Mintzer, I.M. 1987. A Matter of Degrees: The Potential for Controlling the Greenhouse Effect. Washington, D.C. World Resources Institute, Research Report No. 3.

Parry, M.L., T.R. Carter, and N.T. Konjin (eds.) 1988. The Impact of Climatic Variations on Agriculture; Vol. 1: Assessments in Cool Temperate and Cold Regions. Dordrecht: Kluwer Academic Publishers for the International Institute for Applied Systems Analysis and UNEP.

Rayner, S. (ed.). 1993. Global Environmental Change: Special Issue. Vol. 3, No. 1 (March).

Riebsame, William E. 1988. Assessing the Social Implications of Climate Fluctuations. Boulder, Colo.: Natural Hazards Research and Applications Information Center, and United Nations Environment Programme.

Robinson, J. 1988. "Unlearning and Backcasting: Rethinking Some of the Questions We Ask About the Future" in Technological Forecasting and Scoial Change, Vol. 33, pp. 325-338.

Sewell, W.R.D., D. Macdonald-McGee and W. Locke. 1984. Climate Variability and Change in Canada: Towards an Acceleration of the Social Science Research Effort. Downsview, Ont.: Atmospheric Environment Service, Rept. No. 84-12.

Timmerman, P. 1988. "Weathering Climatic Impacts: The Question of Strategy", unpublished paper from full text of following reference.

Timmerman, P. 1988. "Taking the Initiative: A Policy Submission to the Workshop on the Effect of Global Climate Change on Great Lakes Policies and Institutions" tabled at Chicago meeting of Centre for the Great Lakes, May 5, 1988.

Timmerman, P. 1989. "Everything Else Will Not Remain Equal: The Challenge of Social Research in the Face of a GLobal Climate Warming" in Report of the First U.S.-Canada Symposium on Impacts of Climate Change on the Great Lakes basin. Downsview, Ontario: Canadian Climate Centre, Joint Report No. 1 with U.S. National Climate Program Office.

Timmerman, P. and A.P. Grima. 1985. Climate Impact Assessment in the Great Lakes basin: Overview and Research Recommendations. Toronto, Ontario: Institute for Environmental Studies, University of Toronto, IES Monograph No.7.

Timmerman, P. and A.P. Grima (eds.). 1988. Economic Perspectives on the Impact of Climate Variability and Change. Downsview, Ontario: Atmospheric Environment Service, Climate Change Digest Report, CCD 88-04.

U.S. Environmental Protection Agency. 1989. The Potential Effects of Global Climate Change on the United States - Report to Congress. Washington, D.C.: Office of Policy, Planning, and Evaluation.

SELECTIVE HISTORY: CLIMATE SOCIO-IMPACT ASSESSMENT

PRELIMINARY:

HIPPOCRATES
MONTESQUIEU
HUNTINGDON

FIRST GENERATION
(1945-1965)

CONCEPTUALISING CLIMATE

ASSIMILATING BASIC "WEATHER" DATA

LOCAL, ACUTE EVENTS

SECOND GENERATION
(1965-1985)

Phase 1:

INITIAL DATA LINKS (e.g. AGRICULTURAL IMPACTS)

NATURAL HAZARDS WORK

HISTORICAL/SOCIAL THEORY (e.g. CLARK UNIVERSITY)

Phase 2:

INTERDISCIPLINARY

INITIAL COMPUTER MODELS FOR SOCIAL PROCESSES

MAJOR STUDIES

INITIAL POLICY FRAMEWORKS (e.g. VILLACH)

THIRD GENERATION
(1986 +)

DETAILED COMPUTER MODELLING

STRATEGIC PERSPECTIVE

POLICY ISSUES BECOME PART OF PUBLIC AGENDA

Figure 1. Three generations of research

Table 13. Adaptive Responses: Timing and Sector-specific Strategies for Agriculture

Nature of Response	Soil and Water Management	Crop Choice, Husbandry and Land Use	Economic Adjustments
Accommodation: acceleration of current trends at same rate as climate changes	Soil conservation: *e.g.*, terraces, zero tillage, mulching, dry season cover Water management: *e.g.*, irrigation (with varying quantity and timing), soil drainage, mulching, fallowing, crop rotation	Crop choice: *e.g.*, new varieties of existing crops, some crop substitution, conversion to/from crops or pasture, nitrogen-fixing crops, livestock types and levels Husbandry: altered rotations, timing of planting and harvest, plant mixed varieties, planting depth, plant density, herbicides, pesticides, fertilizer application Land use: *e.g.*, altered area, choice of locations, changed specialization	Investment: *e.g.*, infrastructure, equipment and machinery, farm inputs, marketing and credit, agroclimatic information Diversification of income: *e.g.*, savings and storage, employment, regional development Economic integration: *e.g.*, off-farm purchases, subsidies Altered consumption: *e.g.*, food, education, health
Planned Resiliency: coping with a range of current and potential climatic variations	As above, but with emphasis on experimentation in a wider variety of sites and climatic conditions	As above, but including developing and experimenting with new varieties and different crops, experimentation across a wide variety of climatic and soil conditions	As above, with effective national and international policies to prevent famine, promote regional food security, and enhance equitable regional economic development
Purposeful Adjustment: specific responses in anticipation of forecast climate	Increased irrigation capacity, capital-intensive soil and water management	Breeding crops specifically adapted to CO_2-enriched atmospheres, heat stress, and other projected changes	Possibly mechanisms to share costs of mitigating the impacts of climate change
Crisis Response: emergency measures adopted after the failure of previous responses	Importing water, rehabilitation of degraded lands	Importation and rapid experimentation with alternative crops and varieties	Disaster relief, bearing the social and economic consequences (e.g., migration, political instability)

2.2 ECONOMIC/SOCIAL IMPACT ASSESSMENT BREAKOUT GROUP PARTICIPANTS

Facilitator: John Kangass, U.S. Army Corps of Engineers
Rappateur: Andrea Ray, NOAA

Rhonda Rhyzner, Unioversity of Michigan
Peter Timmerman, University of Toronto
Ian Burton, Atmospheric Environment Service
Linda Mortsch, Atmospheric Environment Service
Barry Rubin, Indiana University

2.3 BREAKOUT GROUP REPORT

Five Year Research Plan and Products:

1. Integrated Assessment Framework and methodologies (include how to incorporate social dynamics).

2. Public ownership/involvement strategy to be developed (include environmental equity issues).

3. Identification and evaluation of a range of usable, understandable options for users, decision makers, and the public.

4. Probable impacts across sectors in human and economic terms in appropriate regional context (include identification of sensitive sectors).

5. Response scenarios generated from impact analysis above.

6. Develop institutional capacity to support process of implementing recommendations (invest policy makers in continuing process).

Years 1-2:
- Develop integrated assessment framework (identify "targets" e.g., community development, shoreline issues
- Develop public involvement (e.g., advisory board to bring in regional expertise, "ownership" in process.

Years 3-5:
-"run" assessments, develop range of options and impacts
- institutionalize framework

Critical Issues

A. Assessment Framework (AF)

1. Development of integrated AF.
2. Protocols for model use.
3. Identify science variables, importance for economic, policy analysis.
4. Develop vertical and horizontal linkages in AF (include regional consultation).
5. Understand human adaptation and behavior (for economic sectors, demographics).
6. Public evaluation of response options (based on their value structures).
7. Shoreline risks and uses (change in flood/erosion hazards, insurance, public ownership, etc.).
8. Risk assessment.
9. Identify potential impacts not previously experienced.
10. Enrich scenarios for alternative futures.
11. How (and value of) local and regional responses tie to global framework.

B. The "Public"

1. Public interpretation of meaning of climate change.
2. Inform public on science of assessment framework.
3. Encourage, strengthen public understanding, ownership.
4. Political persuasion in anticipation of uncertainty.

C. Both

1. Understand benefits, opportunities and risks of climate change to stakeholders.
2. Implications for community development in region, uniqueness of Great Lakes basin.

Research Objectives

A. Timeframe

1. Years 1-2 develop assessment framework.
2. Years 3-5 apply assessment framework.

B. Objectives

1. How to bring policy into the evaluation process (not static, sets framework for decision).
2. How to bring social science into framework ("people friendly" evaluation, a la "Sim City"); adaptive behavior, meaning of climate change.

3. Macro scale economics.
   a. identify sectoral expertise.
   b. develop benefit cost or best case? without climate change (do nothing or baseline).
   c. establish integration targets, models, and policy.
   d. establish committee framework of scientists, stakeholders, include regional consultation.

4. Micro scale economics (develop integrated assesment framework for specific situations)

   a. develop plausible regional climate, ecosystems and habitat changes in form suitable for impact models.
   b. analysis of key economic sectors to determine: key climatic parameters for investment decisions, institutional and legal parameters.
   c. determine ecosystem/habitat impacts/integrity; environmental valuation of large systems.

3.0 ECOSYSTEM AND PUBLIC HEALTH

3.1 ISSUE PAPERS

Climate Change and the Health of the Great Lakes Ecosystem

by
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and
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Abstract

The purpose of this paper is to review the status of ecosystem health of the Great Lakes and to review elements of a research program to understand its relation to potential climate change. Application of the notion of ecosystem health to restoration of physical, chemical, and biological integrity of the Great Lakes relies upon an analogy to human health. Unlike assessment of human health, definition of wellness is more arbitrary and includes value judgments about competing uses of the resources of the Great Lakes. This fundamental uncertainty about the specific indicators and end points for restored ecosystems creates a substantial impediment to integration of water quality and fish management perspectives. Adding potential climate change to this management burden could be more beneficial than first appearances might suggest. We argue that there are several habitat and biological issues that overlap concerns of water quality managers, fish managers, and climate change researchers. By addressing these issues in common, some of the key uncertainties, management needs, and research needs of current management will be clarified. More significantly, explicit incorporation of climate change scenarios will assist managers in balancing short-term against long-term goals. Progress, however, will require the formulation of a new research program designed around the development of a modeling system and decision support framework that enables managers to develop flexible management policies in response to uncertainty and the trade-offs of various user interests.

1. Ecosystem Health of the Great Lakes

Concern with the health of ecosystems has arisen with the adoption of an ecosystem approach to management of natural resources. More holistic than a pollutant-by-pollutant approach to improvement of water quality associated with earlier laws and agreements, The Great Lakes Water Quality Agreement of 1978 committed Canada and the U.S. to a long-term recovery goal of "...restoring and maintaining the chemical, physical, and biological integrity of the waters of the Great Lakes basin ecosystem." Relying on an analogy to human health, the restoration of ecosystem integrity has become synonymous with returning the ecosystems of the Great Lakes to a healthy state. Good health is a desirable system property, and wellness has become a symbolic goal of an integrated, ecologically grounded approach to restoration of the ecosystems of the Great Lakes. Recognizing the abuses of the past 200 years of human activity in the Great Lakes basin, the challenge is to balance ecosystem restoration and maintenance with human development. The necessity of this balance is the fundamental premise of "ecologically sustainable, economic development" advocated by the Brundtland Commission (World Commission on Economic Development, 1987).

Joining ecological restoration and human development, however, requires grappling with interactions at spatial and temporal scales that are beyond human experience. The health of Great Lakes ecosystems is no longer an exclusive function of human activities in the basin. Atmospheric deposition is a major source of toxic contaminants entering the lakes, often with origins far outside the basin (e.g. Eisenreich *et al.* 1981). On a global scale, atmospheric accumulation of CO_2 and other "greenhouse" gases threatens to alter climate, which could have substantial effects on the health of Great Lakes ecosystems. Within the basin, consumptive use of water, demands for recreational opportunities, demands for fishing, and demands for coastal development are tied to the global economy through local effects on social and economic factors. Government institutions charged with management of Great Lakes resources also face challenges that often originate outside their mandates for management action. No agency of government is responsible for restoring and maintaining the health of the Great Lakes, rather responsibility is distributed among a plethora of agencies and jurisdictions. In considering the impacts of global climate change on the health of the Great Lakes, therefore, evaluation of the status of research and impact assessment and of the needs for new initiatives must start with recognizing that we begin on uncharted ground. More than new research initiatives will be required to proceed. We may also need better ways of linking research, management, and formulation of public policy to adapt to impending changes on a global scale.

To develop this argument, we will begin with a review of the concept of ecosystem health and proceed to review the status of the Great Lakes, their use impairments, and challenges to management. In section 2, we discuss effects of climate change on ecosystem health by examining linkages and critical issues. Finally, we conclude with an analysis of emerging issues in section 3 and review the elements of a new research program in section 4.

1.1. Concept of Ecosystem Health

In reality, the concept of ecosystem health is often more symbolic than functional. As with human health, maintenance and restoration of ecosystem health admits both curative and preventative approaches. The curative approach finds what is wrong and fixes it while the preventative approach takes a more holistic view and attempts to minimize the risk of illness. Considering human health, the dichotomy of the two approaches yields the current dilemma with technological approaches to medicine--elimination of illness does not necessarily produce wellness. For humans, wellness is a harmony of mind and body, and extensions of the health analogy to ecosystems falters because we lack a definition of wellness. In the context of ecosystem management, not only do we face the causality problem (i.e. finding what is wrong and fixing it), but we also lack clear guidance about the nature of a healthy ecosystem.

One approach to resolving this uncertainty is to consider the adaptive potential of ecological communities. Within constraints of habitat characteristics and climate variability, undisturbed ecological communities tend toward nominal cycles that are characteristic of various ecosystem types. Climax communities of terrestrial ecosystems, as with their analogs in the aquatic communities of the Great Lakes (cf. Loftus and Regier 1972), exist in balance with patterns of disturbance, which reset community composition to some earlier succession stage that returns to the nominal or climax state. Nominal, succession transients are thus common elements to all "healthy" ecosystems, and a concept of community health must include reference to the persistence of the nominal state as mediated by functioning feedback mechanisms. The adaptive properties of ecological communities are manifestations of this ecosystem homeostasis. As Rapport (1990) states, ecosystem health depends upon the integrity of the homeostatic mechanisms, and "integrity refers to the capability of the system to remain intact, to self regulate in the face of internal or external stresses, and to evolve toward increasing complexity and integration."

Unfortunately, specification of the nominal state of an ecological community is somewhat arbitrary. Although Ryder and Kerr (1990) argue that natural ecological communities do tend to evolve toward co-adapted or "harmonic" assemblages, chronological colonization and invasion patterns are accidental, and multiple nominal states could evolve given slightly different composition of colonizing species. This issue becomes especially important when ecosystem restoration is the main challenge as in the Great Lakes. The original ecological communities no longer exist, and many exotic species have established viable and at times dominant populations. Preference for specific nominal states may be guided by historical analysis (e.g. Ryder 1990), yet alternate states are certainly possible. At some level, the decision about which nominal state to pursue in restoration becomes a social preference. Scientific notions may contribute to the decision, but ultimately people must decide what their objectives are for ecosystem restoration and maintenance. Hence, what constitutes "ecosystem health" is, in part, a value judgment.

Despite the ambiguities involved, identification of a "healthy" state of an ecosystem is absolutely required for effective restoration and management of ecosystem health. Without a clear goal, curative actions become an end in themselves. The unintended consequences of uncoordinated management actions could be even more destructive than the problems being solved. Only long-term commitment to restoration of the Great Lakes will ultimately succeed in overcoming the legacy of abuse of the Great Lakes. Without the guidance of a "healthy" state, managers will have difficulty in establishing priorities for allocation of scarce resources for remediation. There is already ample evidence that government agencies work at cross purposes. Due to their differences in perceptions of problems and preferences for restored state, management agencies frequently produce conflicting management plans for Great Lakes resources.

As the scale of problems increases with the advent of global climate change, the adaptive scope of ecosystems and human institutions will face even greater challenges. Responding to these challenges will require better integration of research, management, and policy formation. Given the uncertainties and gaps in knowledge, we must in humility acknowledge that we cannot truly manage ecosystems. Rather, we must manage human activities in the context of ecosystems, which support us. Only from this orientation can we begin to improve the health of the Great Lakes. Realizing that pre-Columbian states of the Great Lakes ecosystems represented one definition of a "healthy" ecosystem, an interim goal for restoration could be re-establishment, to the maximum possible extent, of natural communities.

1.2. Status of the Great Lakes

Assuming that the historical conditions of the Great Lakes are acceptable targets for restoration, the Great Lakes as a whole are unhealthy. Many types of indicators show the current, degraded condition of all of the Great Lakes (e.g. Koonce 1993). Of these indicators, only the lake trout surrogate indicator (Ryder and Edwards 1985) has been systematically applied to the Great Lakes. As documented in Edwards *et al.* (1990), this indicator is a composite index, which is derived from a wide range of conditions necessary to sustain healthy lake trout stocks. The rationale for the use of lake trout as a surrogate for ecosystem health is based on the notion that lake trout niche characteristics and historical dominance in the Great Lakes provide the best basis to detect changes in overall ecosystem health. The index is based on scores from a Dichotomous Key of questions about lake trout or their habitat. A score of 100 indicates pristine conditions. For the period 1982-85, Edwards *et al.* (1990) indicate that Lake Superior (70) had the highest score followed by Lake Huron (59), Lake Ontario (46), Lake Michigan (45), and Lake Erie (39).

These scores are influenced by several factors. Marshall *et al.* (1992) reported on Lake Superior historical and expected future trends in the lake trout indicator for the period 1950 to 1995. The overall value of the indicator showed a decline through the mid-1960s with a projected recovery to 1950 levels by 1995 (Figure 1). Ryder (1990) argues that this recovery pattern indicates that recovery to near pristine conditions is a reasonable goal. In an independent effort, Powers (1989) applied the Dichotomous Key to explore trends in the ecosystem health of Lake Superior and Lake Ontario. Her conclusions were similar to the findings of Marshall *et al.* (1992) for Lake Superior, but she found that Lake Ontario's trends indicated substantial and continuing imbalance.

Powers (1989) explored the possible effects of various fishery management schemes on the future health of the lake. In 1973, the indicator showed a degraded state, and ecosystem health appeared to decline through 1983 in spite of a rather substantial recovery of recreational fishing (Figure 2). Future projections showed a recovery to the 1973 level as rehabilitation of lake trout approached the goals set in the Lake Trout Rehabilitation Plan for Lake Ontario (Schneider et al., 1983). In spite of achieving some of the interim goals for lake trout rehabilitation by 1988, the system health of Lake Ontario resists exceeding the degraded condition in 1973. Over the period 1973 to 1988, lake trout population and other salmonid populations have increased markedly due to intensive stocking efforts. The indicator implies that this rehabilitation effort decreased system health. In a way, lake trout restoration provided an indication of just how degraded the Lake Ontario ecosystem really was.

1.3. Health Impairments

The impaired health of the Great Lakes is due to many factors. The integrity of an ecosystem is a function of the health of its constituent populations, the biological diversity of its ecological communities, and the balance between ecological energetics and nutrient cycling. A healthy ecosystem invokes a vision of healthy populations of fish and wildlife species that interact in a predictable and resilient system governed by fundamental principles of ecological energetics and biogeochemical cycling of matter. In the Dichotomous Key (Edwards *et al.* 1990), impairments are associated with four classes of environmental stresses:

- exploitation and production (including impairments of fish population structure due to over-fishing);
- biotic environmental (alteration of fish community structure due to invasion of exotics, loss of species, etc.);
- abiotic environmental (impairments of trophic status, flow regimes, temperature regimes, etc.); and
- contaminants (toxic contaminant burdens sufficient to cause disease or illness in fish and wildlife population or to pose a threat to human consumption).

In all cases except Lake Erie, contaminants are an important cause of lower indicator values (Figure 3).

Other indicators of ecosystem function also reveal impairments to portions of the Great Lakes. Biomass size spectrum studies of Lake Michigan (Sprules *et al.* 1991) have shown promising results for the use of particle-size spectra in analyzing food web structure. Sprules *et al.* (1991) found that piscivore biomass was lower than expected. The imbalance in the food web appears to be limited availability of prey fish production to the mix of stocked piscivore species. Zooplankton size distribution, as a component of the biomass size spectrum, also indicates imbalance between planktivory and piscivory. According to the Lake Ontario Pelagic Health Indicator Committee (Christie 1993), a mean zooplankton size of 0.8 to 1.2 mm would indicate a healthy balance in the fish community. Over the period 1981 to 1986, the observed range of mean size of zooplankton was 0.28 to 0.67 mm (Johannsson and O'Gorman 1991), indicating excess planktivory. Emerging evidence for 1993, however, suggests that Lake Ontario may be undergoing an abrupt shift in zooplankton size with a collapse of the dominant prey fish population (E. L. Mills, Cornell University, personal communication). The recent trends in Lake Michigan and Lake Ontario may suggest that declines in productivity of both lakes associated with reduced phosphorus loading make these systems less able to sustain predator stocking levels that were successful earlier. Recent modeling studies of Lake Michigan and Lake Ontario (Stewart and Ibarra 1991; and Jones *et al.* in press) indicate a strong possibility that excessive stocking of predators is de-stabilizing the food webs in these ecosystems.

Composite indices other than the Dichotomous Key have also been applied to portions of the Great Lakes. Ohio EPA, for example, has attempted to characterize the state of the estuarian fish communities in Ohio waters of Lake Erie (Thoma, unpublished report, Ohio EPA). Using an Index of Biotic Integrity (IBI), Ohio EPA found that only one of fourteen estuaries sampled met minimal integrity and health criteria (Figure 4). Extensive habitat modification, point source discharges, and diffuse, non-point source effects preclude most sampled sites from attaining minimal goals, but the most serious degradation is the modification of wetlands in the estuaries (Thoma, unpublished report).

By far the most serious impairment of health of Great Lakes, however, has been the loss of genetic and species diversity from fish communities. Through over-exploitation, habitat destruction, and invasion of exotic species, many populations of native species have become extinct or seriously depleted. Christie (1972) documents the major role of over-fishing in destabilizing the fish community of Lake Ontario. The disruption of Lake Erie's fish community (Nepszy 1977) is an example of the interaction of eutrophication and over-exploitation with the extinction of blue pike, which was indigenous to Lake Erie and Western Lake Ontario, virtual extinction of other native species, and establishment of non-native species such as smelt and white perch. Over-exploitation and invasion of sea lamprey had similar effects on Lake Michigan (Wells and McLain 1973), Lake Huron (Berst and Spangler 1973), and Lake Superior (Lawrie and Raher 1973).

Throughout the Great Lakes, the interaction of exploitation and invasion of exotic species has proven to be extremely disruptive. The invasion of sea lamprey into the upper Great Lakes resulted in the demise of lake trout in Lake Michigan and Lake Huron and the loss of a number of lake trout stocks in Lake Superior before an international program for the control of sea lamprey was begun in the 1950's (Smith and Tibbles 1980). The extent of the disruption of the food web by sea lamprey and more recently by zebra mussels and the spiny water flea have led to recommendations for more stringent controls on introductions (IJC and GLFC 1990). Mills *et al.* (1993) document 139 non-indigenous species that have become established since the 1980s. Although few of these species have had the disruptive impact of sea lamprey or zebra mussels, they have a cumulative effect on the structure of aquatic communities of the Great Lakes, and their persistence raises substantial problems for the rehabilitation and maintenance of native species associations.

1.4. Management Challenges

Degradation of the health of the Great Lakes originates in multiple assaults on physical, chemical, and biological integrity of the constituent ecosystems. Restoration depends upon reversing these effects, but future coordination of management activities will require the evolution of a new strategic-planning initiative. Although Federal, State, Provincial, and Tribal agencies have varied management authority for areas of the Great Lakes, ecosystem management requires coordination of management across the basin. Two agreements, the 1955 Convention on Great Lakes Fisheries and the 1978 Great Lakes Water Quality Agreement (GLWQA), commit Canada and the U.S. to common management. Fisheries agencies under the auspices of the Great Lakes Fishery Commission have pursued their common management through the 1980 Strategic Plan for Management of Great Lakes Fisheries (SGLFMP). SGLFMP calls for the development of fish community objectives and environmental objectives for each of the Great Lakes. In practice, however, the fish community objectives arise from a concern only with managing the open-water fish stocks (i.e. stocks of common concern).

The GLWQA seems to have a broader reach. The goal of the agreement is to restore the physical, chemical, and biological integrity of the Great Lakes. The 1987 Protocols of the GLWQA also call for the development of ecosystem objectives for each of the lakes, but the agreement is implemented by water quality agencies (USEPA, Environment Canada, and various State and Provincial environmental protection agencies). In contrast to fish managers, water quality managers focus primarily on regulations that deal with human activity along tributaries and near-shore areas.

These two approaches often originate from quite different value perceptions. Because of their mandate and demands of their resource users, fish managers are committed to provide sustainable fisheries in the Great Lakes. Their objective is to provide as much harvest for recreational and commercial fisheries as is possible under prudent management. Water quality management, in contrast, pursues a goal of restoring the physical, chemical, and biological integrity of the Great Lakes. In this context, fishing could be considered just another stress and not a beneficial use to be maintained. Nowhere is this conflict clearer than in the disagreement about the wisdom of further reductions in phosphorus loading to Lake Erie. Fish managers are worried that further reductions will lower productive capacity of the fisheries unnecessarily, and water quality managers are committed to attaining a level of phosphorus loading that will minimize the risks of anoxia in the Central basin hypolimnion.

Various indicators clearly show that the state of the health of aquatic communities of the Great Lakes do not satisfy the ecosystem objectives adopted by Canada and the United States (Koonce 1993). Although some of these indicators show signs of improvement, it will be difficult for managers to agree on quantitative specification of endpoints for the indicators that will specify attainment of ecosystem objectives. The goal of the GLWQA is to restore and maintain the integrity of the ecosystems of the Great Lakes. Until now, there has been an assumption that specification of ecosystem integrity is largely a scientific or technical issue. The extent of historical disruption of aquatic communities and the establishment of large numbers of non-indigenous species, however, may preclude the use of native associations (i.e. pre-settlement ecosystems) as benchmarks for ecosystem integrity. At best, scientific analysis will allow specification alternative configurations of the structure of aquatic communities in the Great Lakes that are consistent with fundamental ecological principles. The ultimate selection of a restored state is thus a matter of social preference. Because social preference for state of the Great Lakes ecosystems embodies an implicit set of uses, the specification of quantitative end points for the indicators is tangled in the determination of acceptable ways of using the resources of the Great Lakes. Ecosystem objectives, which have been developed under the mandate of the GLWQA (Bertram and Reynoldson 1992), do not address the issue of how to balance the various uses of these resources, and managers may find future progress toward attaining the goals of the GLWQA impeded by the lack of consensus on the desired state of aquatic ecosystems. If managers cannot overcome this impediment, they will not be able to measure the "wellness" of the Great Lakes relative to the desired restoration goal of healthy ecosystems.

At the present time, no institutional framework exists for ecosystem management. Without such a framework, strategic planning for integrated management of the Great Lakes will face many institutional impediments. The most important element in a strategic plan is the strategic vision, which is an explicit statement of the desired state of ecosystem health in the Great Lakes. The current institutional milieu has enough difficulty resolving value conflicts. More difficult problems lie ahead. For example, managers have yet to find a way of dealing with uncertainties in the domain of global change. Global climate change has the potential to reverse or impede some restoration efforts, but it is not clear how to initiate strategic planning to preserve flexibility in the face of uncertainty and to resolve value conflicts simultaneously. In the absence of such a strategic planning effort, management activities will be dominated by short-term reactions to emerging problems rather than an active adaptation, which could prevent future erosion of efforts to restore ecosystem health of the Great Lakes. We return to this point in section 3.

2. Effects of Climate Change and Climate Variability

Despite the difficulties in developing common objectives for the restoration of health of the Great Lakes, management agencies share concern with some habitat issues. These issues are also important linkages to understanding the possible effects of global climate change on ecosystem health. The issues concern suitability of four habitat types:

- Tributaries,
- Near-shore (wetlands and littoral zone),
- Offshore hypolimnetic zone, and
- St. Lawrence and Gulf of St. Lawrence system.

Much of the deterioration of the health of the Great Lakes has been caused by destruction of the physical and chemical integrity of these zones. The Areas of Concern identified in the 1987 Protocols of the GLWQA, for example, are largely degraded tributary and embayment systems.

2.1. Linkages

<u>Tributaries.</u> A major component of the loss of biodiversity in the Great Lakes is associated with the extinction of adfluvial species, i.e. species that require river environments for spawning and nursery areas. Dam construction, channelization, sedimentation, alteration of hydraulic and temperature regimes, and contamination with toxic substances have eliminated important habitat for historically important species such as lake sturgeon, brook trout, Atlantic salmon, walleye, and sauger. Restoration of tributary habitat, including possible dam removal and installation of fish-passage devices is under active consideration throughout the Great Lakes basin. Suitability of tributary habitat, however, is very sensitive to hydraulic and temperature regimes. Climate change is likely to have significant impact on precisely these attributes.

<u>Near-shore environment.</u> The near-shore environment of the lower Great Lakes has also been extensively modified by coastal development. Near-shore wetlands and macrophyte beds in embayments are also important habitat for fish and wildlife. The most serious impacts have followed wetland destruction through drainage and diking.

Efforts to preserve remaining wetlands are underway, but the patchwork pattern of preserved areas may be insufficient for wetlands to adapt to changing regimes of water levels. Similarly, hardening of the near-shore environment with jetties, armor stone, and bulkheads decreases its capacity to serve as spawning and nursery areas for some species. This coastal development also limits the capacity of natural shorelines to adapt to changing flow and water level regimes in a way that minimizes adverse effects on fish and wildlife populations.

Off-shore environment. On the whole, offshore areas are likely to be less sensitive to climate change than other habitats. The exception will be the Central basin of Lake Erie. El-Shaarawi (1987) has shown that water level, water temperature, and phosphorus loading are the controlling factors for oxygen depletion in the Central basin of Lake Erie. Before their extirpation, blue pike occupied the cool waters of the Central basin. Their production was a mainstay of the commercial fishery for many years prior to 1955. This habitat is now being recolonized by walleye, and it is possible that a deep water percid could become reestablished. The risk of hypolimnetic anoxia, however, is sensitive to climate factors (water level and rate of warming in the spring). Phosphorus loading targets accepted under the GLWQA agreement may not be appropriate for all climate change scenarios.

St. Lawrence and Gulf of St. Lawrence. Of all the stresses that have led to impairments of Great Lakes health, invasion of exotic species have led to the most damage. Of the 139 non-indigenous species documented by Mills *et al.* (1993), nearly a third entered via the St. Lawrence River. Most of these were associated with shipping (e.g. ruffe and zebra mussels), but many of the non-indigenous fish species such as alewife, white perch, and possibly sea lamprey invaded the Great Lakes from the Atlantic drainage of the St. Lawrence. The location of the Gulf of St. Lawrence is northern enough to isolate the Great Lakes from other anadromous species such as striped bass. Global climate change could, however, affect ocean circulation patterns and lead to more invading species. The population explosions of alewife and white perch have been associated with depressed predator populations. Although a "healthy" Great Lakes ecosystem is no guarantee of resistance to invasion, the effects of new invasions is likely to be less severe than if the aquatic communities remain degraded.

2.2. Critical Issues

These potential linkages between climate change and ecosystem health suggest five critical issues for further examination:

- Invasions of exotic organisms through the St. Lawrence;
- Alteration of hydraulic regimes of tributaries;
- Alteration of thermal regimes of tributaries;
- Alteration of flows, water levels, and water level fluctuations; and
- Adaptive potential of near-shore environments.

The last four issues have analogies in restoration of terrestrial ecosystems such as the Oak Savannah. Ideas emerging from landscape ecology are emphasizing the importance of understanding not only amount of land in conservation and restoration areas, but also the spatial pattern of the areas.

3. Emerging Issues

The previous five issues are important to understanding the potential effects of climate change on ecosystem health, or more properly, on plans to restore ecosystem health. In addressing these uncertainties, a number of other issues are likely to emerge. Table 1 lists some candidates for further consideration.

Table 1. Uncertainties, management needs, and research needs that are likely to emerge from a more explicit consideration of the effects of climate change on the health of Great Lakes ecosystems.

3.1. Key Uncertainties
- How much restored tributary habitat is enough?
- What are the effects of community structure on success of invading species?
- What is the role of water level fluctuations in the maintenance of wetland and near-shore macrophyte assemblages?
- Are there effects of wetland and submerged aquatic vegetation patch size and connectedness that determine the resilience of near-shore environments to variation in water level and fluctuations in water level?

3.2. Management Needs
- Need for cooperative management (water quality, quantity, and biological management authorities are currently vested in separate agencies)
- Need common visions for future state of Great Lakes--a public consensus forged with explicit consideration of trade-offs
- Need for explicit consideration of uncertainty of global change
- Need for a method to evaluate worth of information in the development of policy.

3.3. Research Needs
- Effective presentation of climate change information to managers
- Evaluation of flexibility of management policies and worth of information
- Evaluation of public participation and education initiatives to assist the development of common vision for the long-term health of the Great Lakes

4. Elements of a New Research Program

We believe that the consideration of the possibility of climate change should become a part of all long-term management programs where it could offset the feasibility of achieving program goals. Although current efforts to develop long-term management plans for the Great Lakes are encountering difficulty in developing a common vision of restored health of the Great Lakes, an attempt to incorporate possible climate effects might have that advantage of casting the problem in a new light. We have argued (Hobbs *et al.* 1993) that because climate change will have both biophysical and socioeconomic impacts, managers must evaluate the trade-offs and risks of adaptive responses to these impacts. This evaluation, however requires understanding of the linkages and feedbacks of climate change and ecosystem health. These are complex problems and will undoubtedly require modeling systems and decision frameworks with which decision makers, managers, and other interested parties might game and, thereby, develop a better insight into system behavior.

Inclusion of climate change in the trade-off analysis for management of health of the Great Lakes must begin with a research program designed around the development of a modeling system and decision support framework. Our approach to this problem (Hobbs *et al.* 1993) has been based on two questions:

1. "Given the uncertainties surrounding climate change, how can the flexibility of Great Lakes management policies and the worth of climate information be evaluated?" and,
2. "Can such a model and decision framework help users to better understand the implications of climate change for Great Lakes management?"

To be effective, the research program must be linked to management concerns and involve managers in project design, execution, and evaluation. In the end, precise numerical predictions from the models may be less important than the trends and the conflicting consequences of policy options preferred by various stakeholders or interest groups. The multicriteria decision making aids that will emerge from considering climate change, therefore, also offer the opportunity to explore resolution of the current impediments to implementing integrated management of ecosystems of the Great Lakes.

Below we describe several Great Lakes management decisions for which information on climate change and its implications for ecosystem health might be relevant. Each decision has the following characteristics:

- One or more options that involve an irreversible, or costly to alter, commitment of resources;
- The benefits and costs, both in economic and ecological terms, of those options would be altered by climate change;
- Such resource commitments can be delayed, allowing managers to obtain more information on the likelihood and nature of climate change;
- But delays in commitments also mean that some interim benefits will be foregone.

Such decisions are different from the type described by Rogers (1991), in which small increments of capacity are added to a system in order to meet growing demand. Examples of the latter type of decisions include capacity expansion for water supply systems, electric utilities that use one type of fuel, or quotas for harvest of fish populations. Near-term capacity decisions are unlikely to be altered by the prospect of climate change several decades down the road, since the timing and size of later additions can be altered as the effects of climate change become clear. The management decisions we discuss below are different; what is done now can significantly affect benefits and costs later, and corrections of errors may be expensive.

Lake Levels Management. One question faced in the recent IJC Lake Levels Reference Study was: ought we invest a billion dollars or more in control structures for Lakes Erie, Huron, and Michigan? Climate change would significantly decrease the value of regulatory structures for preventing flooding and erosion because lake levels would drop. On the other hand, a climate change induced decrease in Lake Erie's level would exacerbate anoxia problems in the Central basin; regulation could mitigate some of that change. Figure 1 illustrates an analysis we performed of that impact in reference to the effects of a flow regulation structure at two possible levels of climate change.

Shore Protection. The question here is: what type of investments ought to be made to prevent flooding and erosion? If lake levels drop because of climate warming, then the benefits of the more permanent of such investments might decrease, diminishing their attractiveness. On the other hand, the lessened ice cover that warming would bring might enhance their value. The consequences of such decisions for shoreline habitat have already been discussed above. As in lake levels management, delaying decisions would allow the likelihood of climate change to be better assessed before making a commitment, but might also mean continued damages.

Navigation. A question managers might face is: if lake levels might drop precipitously, are there harbors and channels for which the increased dredging cost would not be justified by the benefits of keeping them open? When would we know enough about the effects of climate change on the Great Lakes to decide to cease dredging some areas? These decisions have ecological implications in terms of dredged material disposal and resuspension of toxic materials in sediments.

Wetlands. If lake levels drop, then many wetlands will be destroyed, but others will be created. At what point should we allow threatened wetlands to be converted to other valuable uses? Alternatively, when might diking and other strategies for wetland preservation be justified?

Contaminated Sediments. Decreases in lake levels could expose contaminated sediments to resuspension. This possibility could alter decisions being made today concerning remediation (Rhodes and Wiley 1993).

Fisheries Management. If the climate change leads to severe changes in the hydraulic or temperature regimes of tributaries or other critical habitat, it may not be possible to sustain populations of certain species in which we are presently investing resources or in which we plan to invest resources. At what point might it be concluded that climate change is so likely that we should shift our emphasis to species that are likely to fare well in a warmer climate?

We agree with other researchers (e.g., Fiering and Rogers in press; Yohe 1991) that much insight is to be gained by analyzing management decisions under climate uncertainty using the tools of decision trees and Bayesian analysis. In the decision tree methodology, explicit recognition is made of the range of possible outcomes and of when decisions are made and knowledge acquired. Such an approach allows for explicit quantification of the worth of information and the value of flexibility strategies that leave options open.

Figures

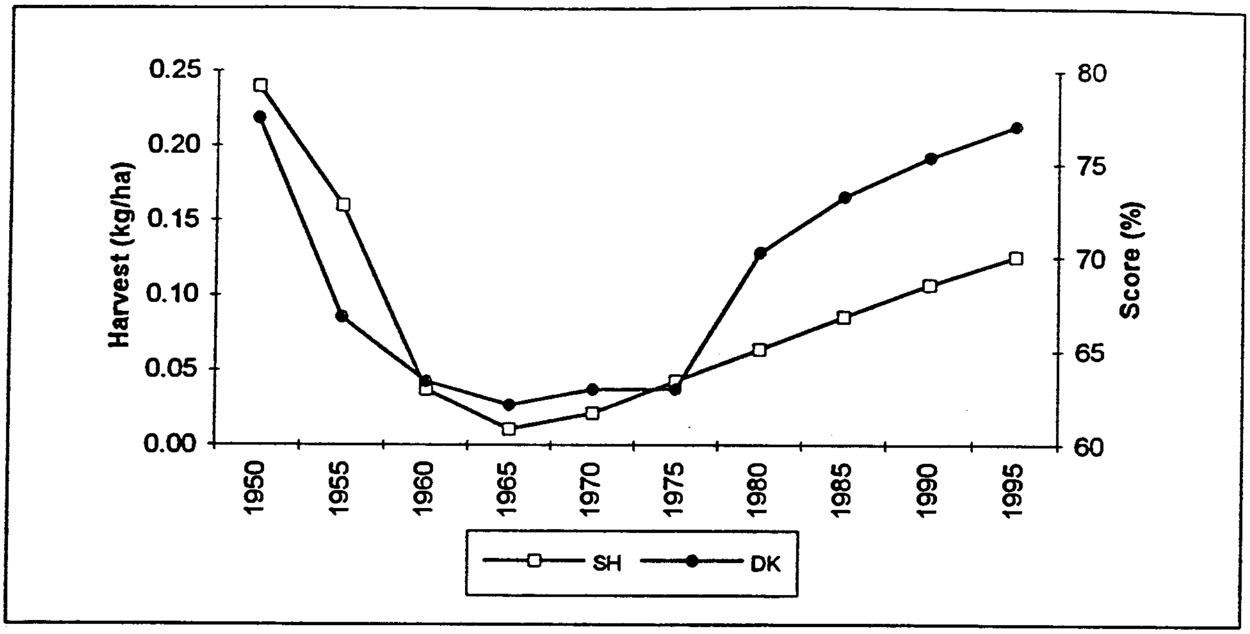

Figure 1. Comparison of annual harvest of all salmonines in Lake Superior with score from the Dichotomous Key. Figure is after Marshall *et al.*, 1992, p. 65.

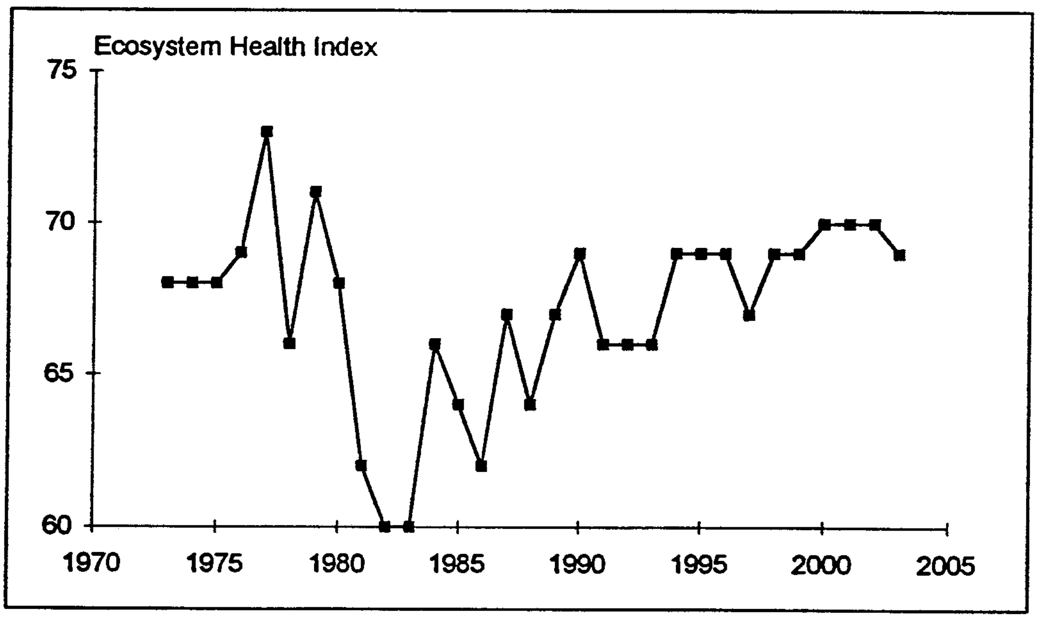

Figure 2. Estimated ecosystem health index for Lake Ontario for the period 1973 to 2002. Ecosystem health index values were derived from the Dichotomous Key of Ryder and Edwards (1985) by a recursive procedure (Powers 1989).

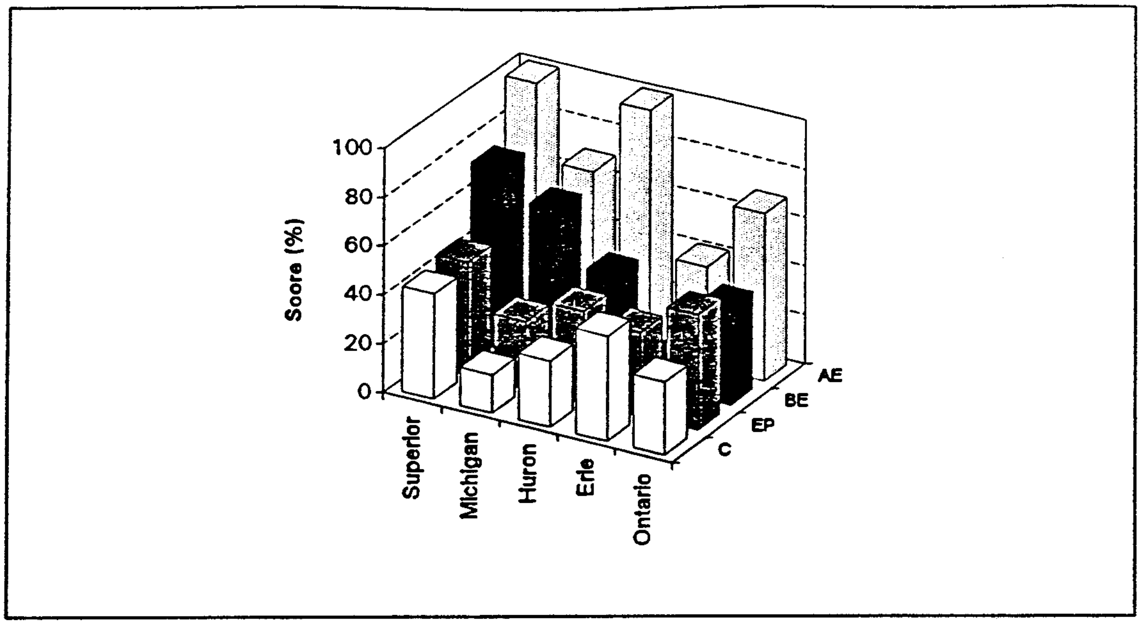

Figure 3. Contribution by stress category to Dichotomous Key scores for each Great Lake for 1982-85. Codes for stress categories are C (Contaminants), AE (Abiotic Environment), BE (Biotic Environment), and EP (Exploitation and Production). Data are after Edwards et al. 1990, p. 602.

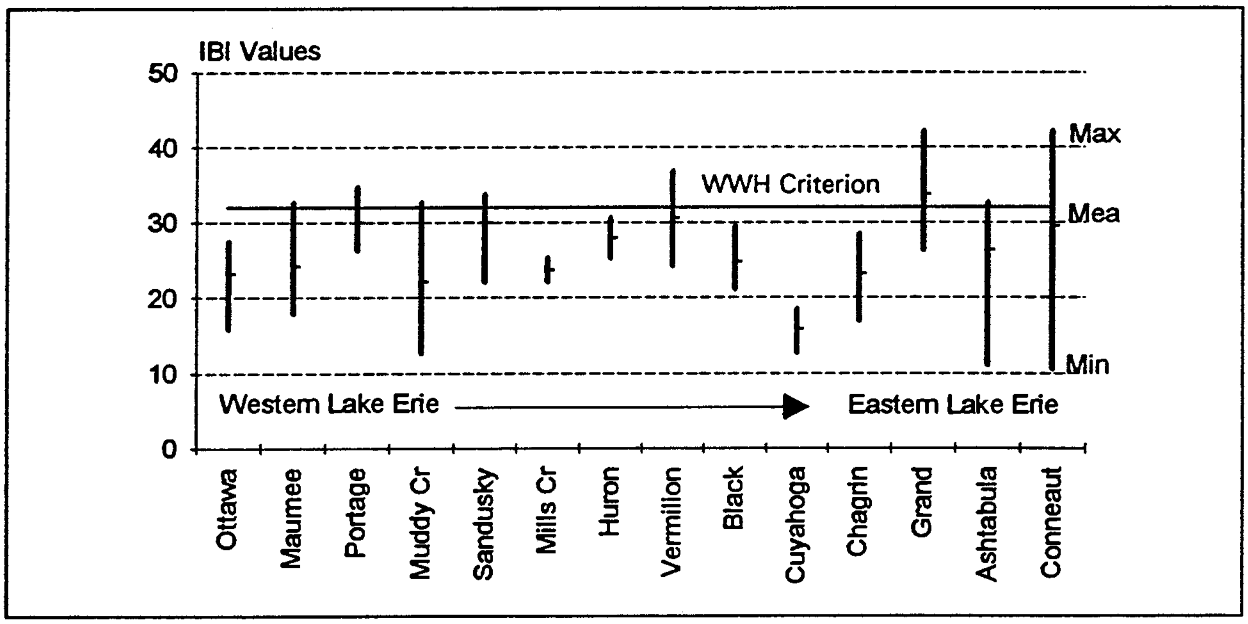

Figure 4. Minimum, maximum, and mean Index of Biotic Integrity (IBI) for 14 estuaries in Lake Erie. For comparison the Warm Water Habitat aquatic life use criterion value of 32 is plotted as a solid line. Figure is from Thoma (unpublished report, Ohio EPA).

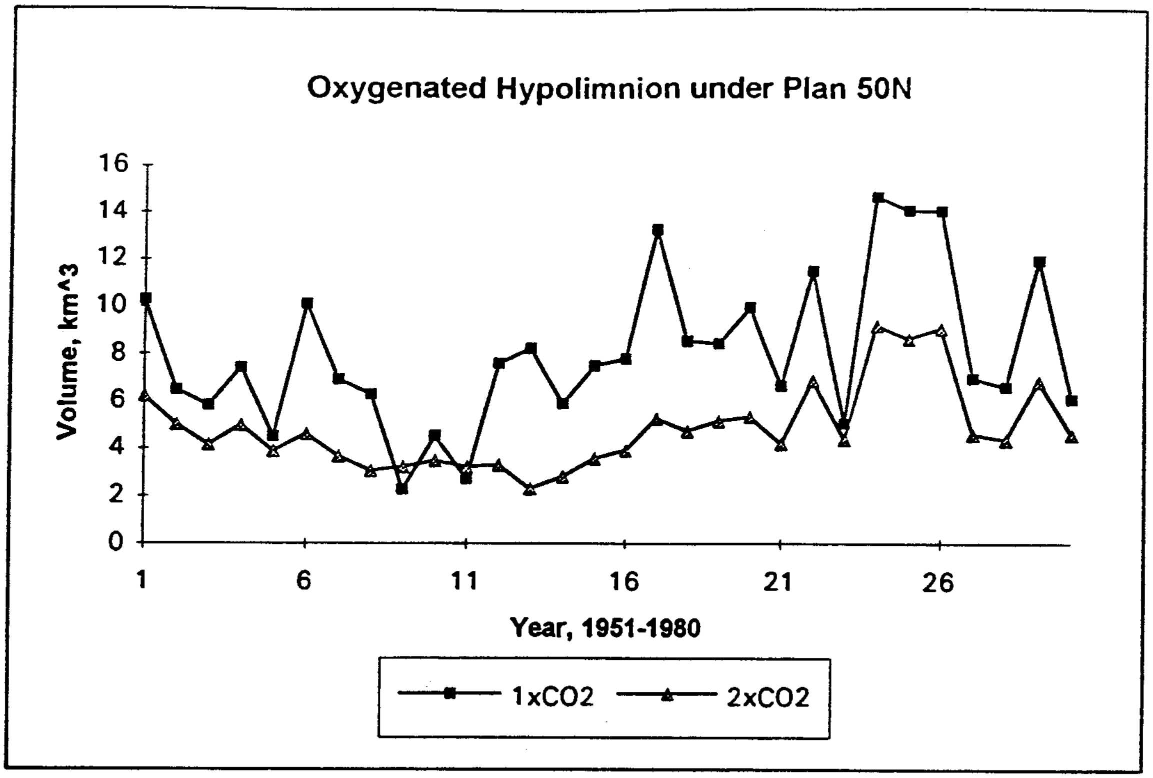

Figure 5. Comparison of the expected effects of two levels of atmospheric CO_2 on volume of oxygenated hypolimnion in the Central Basin of Lake Erie. These results are for historical simulations to judge the effects of a flow control structure (50 N) on the Niagara River (after Hobbs *et al.* 1992).

Literature Cited

Bertram, P. E. and T. B. Reynoldson. 1992. Developing ecosystem objectives for the Great Lakes: policy, progress and public participation. J. Aquat. Ecosys. Health 1:89-95.

Berst, A. H. and G. R. Spangler. 1973. Lake Huron--The ecology of the fish community and man's effects on it. Great Lakes Fish. Comm., Tech. Rep. 21. 41 pp.

Christie. W. J. 1972. Lake Ontario: effects of exploitation, introductions, and eutrophication on the salmonid community. J. Fish. Res. Bd. Canada 29: 913-929.

Christie, W. J. [Ed.]. 1993. Lake Ontario: an ecosystem in transition. Report of the Lake Ontario Pelagic Community Health Indicator Committee. Ecosystem Objectives Working Group.

Edwards, C. J., R. A. Ryder, and T. R. Marshall. 1990. Using lake trout as a surrogate of ecosystem health for oligotrophic waters of the Great Lakes. J. Great Lakes Res. 16:591-608.

Eisenreich, S. J., B. B. Looney, and J. D. Thornton. 1981. Airborne organic contaminants in the Great Lakes ecosystem. Envir. Sci. Tech. 15: 30-38.

El-Shaarawi, A. H. 1987. Water quality changes in Lake Erie, 1968-1980. J. Great Lakes Res. 13:674-683.

Fiering M.B. and P. Rogers, "Climate Change and Water Resources Planning Under Uncertainty," Draft Report, Institute for Water Resources, U.S. Army Corps of Engineers, Ft. Belvoir, VA, in press.

Hobbs, B. F., P. T. Chao, and J. F. Koonce. 1992. Climate change and management of water levels in the Great Lakes. In "Climate Change and Water Resources Management." Proceedings of a Conference Sponsored by USEPA and U.S. Army Corps of Engineers.

Hobbs, B. F., P. T. Chao, and J. F. Koonce. 1993. Potential climate change and Great lakes management: Models, flexibility, and process evaluation. In Mortsch, L., G. Koshida, and D. Tavares [eds.]. Adapting to the Impacts of Climate Change and Variability. Great Lakes-St. Lawrence basin Project. Environment Canada. Workshop Proceedings. p 64-69.

Johannsson, O. E., and R. O'Gorman. 1991. Roles of predation, food, and temperature in structuring the eplimnetic zooplankton populations in Lake Ontario, 1981-1986. Trans. Am. Fish. Soc. 120: 193-208.

Jones, M. L., J. F. Koonce, and R. O'Gorman. in press. Sustainability of hatchery-dependent fisheries in Lake Ontario: the conflict between predator demand and prey supply. Trans. Amer. Fish. Soc. (accepted for publication).

Koonce, J. F. 1993. The State of Aquatic Community Health of the Great Lakes. Special paper for the 1994 State of the Lakes Ecosystem Conference. U.S. EPA and Environment Canada. 34 p.

Lawrie, A. H. and J. F. Raher. 1973. Lake Superior--A case study of the lake and its fisheries. Great Lakes Fish. Comm., Tech Rep. 19. 69 pp.

Loftus, K. H. and H. A. Regier [eds]. 1972. Proceedings of the 1971 symposium on salmonid communities in oligotrophic lakes. J. Fish. Res. Bd. Canada 29:611-986.

Marshall, T. R., R. A. Ryder, and C. J. Edwards. 1992. Assessing ecosystem quality

Marshall, T. R., R. A. Ryder, and C. J. Edwards. 1992. Assessing ecosystem quality through a biological indicator: a temporal analysis of Lake Superior using the Lake Trout Dichotomous Key. In Vander Wal, J. and P. D. Watts [Eds.]. *Making a Great Lake Superior.* Lakehead University. Centre for Northern Studies, Occasional Paper #9. pp: 41-65.

Mills, E. L., J. H. Leach, J. T. Carlton, and C. L. Secor. 1993. Exotic species in the Great Lakes: a history of biotic crises and anthropogenic introductions. J. Great Lakes Res. 19: 1-54.

Nepszy, S. 1977. Changes in percid populations and species interactions in Lake Erie. J. Fish. Res. Bd. Can. 34:1861-1868.

Powers, Melanie S. 1989. An Examination of the Dichotomous Key and the Reliability of its Ecosystem Indicator Measure of System Health, the Lake Trout (*Salvelinus namaycush*), for Lakes Ontario and Superior. M.S. Thesis, Case Western Reserve University. Cleveland, Ohio. 137 p.

Rapport, D. J. 1990. Challenges in the detection and diagnosis of pathological change in aquatic ecosystems. J. Great Lakes Res. 16:609-618.

Rhodes S.L. and K.B. Wiley, "Great Lakes Toxic Sediments and Climate Change: Implications for Environmental Remediation," Global Environmental Change, Sept. 1993, 292-305.

Rogers, P. 1991. "What Water Managers and Planners Need to Know About Climate Change and Water Resources Management," presented at the First National Conference on Climate Change and Water Resources Management, Nov. 4-7, Albuquerque, NM.

Ryder, R. A. 1990. Ecosystem health, a human perception: definition, detection, and the dichotomous key. J. Great Lakes Res. 16:619-624.

Ryder, R. A. and C. J. Edwards [Eds.]. 1985. A conceptual approach for the application of biological indicators of ecosystem quality in the Great Lakes basin. Report to Great Lakes Science Advisory Board. International Joint Commission. Windsor, Ontario. 169 p.

Ryder, R. A. and S. R. Kerr. 1990. Harmonic communities in aquatic ecosystems: a management perspective. In Van Densen, L. T., B. Teinmetz, and R. H. Hughes [Eds.]. *Management of Freshwater Fisheries.* Proc. Sym. EIFAC, Göteborg, Sweden. Pudoc, Wageningen. pp: 594-623.

Schneider, C. P., D. P. Kolenosky, and D. B. Goldthwaite. 1983. A joint plan for the rehabilitation of lake trout in Lake Ontario. Great Lakes Fish Comm. Spec. Publ. 50 pp.

Smith, B. R. and J. J. Tibbles. 1980. Sea lamprey (*Petromyzon marinus*) in Lakes Huron, Michigan and Superior: history of invasion and control, 1936-78. Can. J. Fish. Aquat. Sci. 37: 1780-1801.

Sprules, W. G., S. B. Brandt, D. J. Stewart, M. Munawar, E. H. Jin, and J. Love. 1991. Biomass size spectrum the Lake Michigan pelagic food web. Can. J. Fish. Aquat. Sci. 48:105-115.

Stewart, D. J. and M. Ibarra. 1991. Predation and production by salmonine fishes in Lake Michigan. Can. J. Fish. Aquat. Sci. 48:909-922.

Wells, L. and A. L. McLain. 1973. Lake Michigan: Man's effects on native fish stocks and other biota. Great Lakes Fishery Commission, Tech. Rep. 20. 55 p.

World Commission on Economic Development. 1987. Our Common Future. Oxford

University Press. Oxford, UK.

Yohe, G.W. 1991, "Uncertainty, Climate Change, and the Economic Value of Information: An Economic Methodology for Evaluating the Timing and Relative Efficacy of Alternative Responses to Climate Change with Application to Protecting Developed Property from Greenhouse Induced Sea Level Rise," Policy Sciences, 24, 245-269.

Human Dimensions and the Impact of Global Change on Public Health

by

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Introduction. Human activities have not only made significant contributions to some of the causes of global change in the ecosystem, but are also being affected by its consequences. Therefore, the human dimensions, in terms of causes and effects of global change, cannot be ignored. When examining the effects of global change, one encounters a complex series of interrelationships within the ecosystem. We currently do not have a thorough understanding of the interrelationships between the air, water, and terrestrial compartments of the ecosystem and the physical forces in the environment that attempt to regulate balances between them (e.g., the carbon, nitrogen, and water cycles). In recent years, it is becoming clear that transboundary exchanges of macromolecules are occurring between ecosystem compartments in ways that only now are beginning to be understood. The ecosystem changes that have occurred, or that are expected to occur, involve a complex set of dynamics between the following components of global change: climate alteration resulting from global warming and other factors; population increases and migration to urban areas; environmental pollution related to energy production and other factors; and threats to biodiversity of the earth's flora and fauna as natural areas are increasingly utilized by expanding human needs. Each of these components is related in several ways to human activities and may effect the health status of sectors of the population. The potential effects of global change on public health parameters are important issues that require additional knowledge to assess their long term health effects. This paper will discuss some of the major effects of global change on public health and will identify areas where additional information is needed to fully understand the problems in order to minimize the health effects of global change.

The following two sections will discuss how global change can affect human health. First, some of the indirect effects of global change on human health will be discussed. The latter part of the paper will focus on some of the direct effects of global change on human health such as hyperthermia and recent findings on the effects of exposure to ultraviolet radiation.

Indirect effects of global change on humans. Some of the indirect effects include the influence of climate or atmospheric changes on the quantity or quality of food production. Agricultural output could be affected by shifts in climate which would reduce productivity due to limited water supply, loss of land due to a rise in sea level, wind erosion, or flooding due to excessive rainfall or the mismanagement of rivers and reservoirs. A change in climate could mean a shift in the type of plants used for food supplies. If a species is introduced to a new area, several years may be required for it to get established in its new environment. Introduction of new species brings new risks such as the susceptibility to disease, sharing resources for food and water, and the existence of new predators. Establishment of new species and the continued survival may be dependent on successful resistance to disease in the new region which may take from several years to two decades, or multiple generations to acquire. Therefore, the relatively rapid changes that are taking place today are not favorable for migration or re-establishment of species.

The effects of UV-B radiation on biota other than man. The decrease of the stratospheric ozone shield has resulted in increasing amounts of UV-B radiation to reach the earth. UV-B has the potential to affect plants and animals at all levels of the ecosystem. There is evidence to suggest that UV-B decreases algal biomass production, an important component of the food chain. A significant portion of human populations rely heavily on aquatic and marine sources for food, and significant alterations of the food chain could be devastating. Terrestrial plants may also be affected by UV radiation. The agricultural production of food crops may be affected. Further studies are needed to understand the potential effects of increased amounts of UV-B on agricultural productivity as well as the effects on aquatic systems.

Effects of global change on vector borne diseases. Global change has the potential to modify the current pattern of vector borne diseases in tropical and subtropical regions. The incidence and distribution of diseases like malaria, transmitted by mosquitoes, are dependent on rainfall and tropical temperatures for reproducing in large numbers. Alteration of rainfall and temperature ranges will affect the distribution of these insect vectors as well as many others. In the northern hemisphere, it is anticipated that tropical areas would extend northward and similarly, southward in the southern hemisphere. Scientists associated with the World Health Organization (WHO Task Group, 1990) predict that global warming will expand the areas currently affected by infectious tropical diseases transmitted by insect (as well as other animals) vectors. The spread of parasitic and infectious diseases to additional countries and populations will only add to the burden of caring for the millions already affected by diseases such as schistosomiasis, leishmaniasis, dengue, yellow fever and other infectious diseases dependent on insects or other animals for their transmission.

Direct effects of global change on humans. Potential increases of 1.5 to 4.5°C in mean global temperatures are predicted to occur over the next 40-50 years (WHO Task Group, 1990; Longstreth, 1991). There is good scientific evidence that global warming since the industrial revolution has been occurring at a rate more rapid than ever recorded in human history. There is good reason to believe that increases in the next 50 years will be even greater. The increase in greenhouse gases are mainly responsible for these unprecedented high rates. These global warming effects take into account the nearly 100% increase in CO_2 expected over the next half century plus the contributions of other greenhouse gases, some of which have greater atmospheric heating capacity per molecule (e.g., methane) than CO_2.

Heat Stress and Climatic Change. Heat stress can cause a variety of health related problems (WHO Task Group, 1990). Physiologically, the body reacts to heat stress by changes in cutaneous vasodilatation and fluid imbalance. The result is often edema of the feet and legs. Heat stress can also be accompanied by skin irritations and rashes. Increased fluid intake is necessary during heat stress to replace water loss during sweating and to help maintain body fluids and electrolytes. Salt depletion may lead to cramps and muscle fatigue or anorexia. Electrolyte balance and replacement is imperative for individuals with kidney or cardiac disease. Cases of extreme heat exhaustion can lead to heat stroke where body temperatures reach 41°C (106°F) or higher. These conditions frequently lead to central nervous system dysfunction or coma. Heat stress is known to decrease productivity and susceptibility to injury in occupational settings. Many labor unions have negotiated agreements that mandate halts in production in factories when temperatures exceed certain levels.

Health effects attributed to global change may be difficult to accurately predict (Longstreth, et al. 1991; WHO Report, 1990; Leaf, 1989, McCally and Cassel, 1990; Ewan, et al., 1990; Haines, 1991). Health can be affected by a combination of environmental, hereditary, and social factors. It is not always easy to identify and characterize confounding factors in any of these three areas. However, since global change is expected to be associated with increasing mean global temperatures, the known effects of temperature on heat stress should be examined with respect to human mortality and morbidity.

Heat stress studies have been reported for many parts of the world. The elderly, usually classified as 65 years or older, are most vulnerable to heat stress (Kalkstein, et al., 1987; Davis and Kalkstein, 1990; Kalkstein and Davis, 1989; Kalkstein, 1991; Ewan, et al., 1990). Kalkstein and colleagues have provided a method (Davis and Kalkstein, 1990; Kalkstein and Davis, 1989; Kalkstein, 1991) for synoptically categorizing 28 meteorological variables and pollution indexes into 10 groups. Comparisons of the groups were then made with mortality rates in several U.S. cities. The methods utilized by Kalkstein, et al. (1987) help to differentiate heat stress from air pollution related mortality. Reports of heat related mortality for St. Louis (Kalkstein, 1991) showed that the synoptic category characterized as oppressive tropical heat, had the highest mortality rate. A 1 day lag period exists between the category and the mortality; the elderly and non whites had the highest mortality rates. Studies on heat waves in Australia have also shown the elderly to be most susceptible to heat stress (Gentilli, 1980; Ewan, et al., 1990). The effect on the elderly could be a larger factor in the next century due to the increasing lifespan that will increase the number of people aged 65 and over.

The St. Louis study (Kalkstein, 1991) also found that the duration of a heat wave was an important factor. Several consecutive days of temperatures hovering at 95°F were more harmful that a short duration of 100°F followed by a more moderate and tolerable temperature period. In the St. Louis study, there was not a correlation between air pollution and mortality. The latter observation differs from the conclusions of mortality studies in Los Angeles (Schwartz, et al., 1988) and London (Schwartz. et al. 1987). However, in the latter two studies, the pollution levels were higher than in the St. Louis study. Using models developed by Kalkstein (Kalkstein, et al., 1987) additional retrospective studies can be done to characterize the heat induced mortality. Application of these methods may be helpful in the future to determine when high risk conditions are developing so that preventative actions may be taken.

Recent studies (Smith, et al., 1992) reveal teratogenic effects on the fetus following maternal hyperthermia. In this study, neural tube defects were reported in embryonic development in humans and Guinea pigs. Most embryos with gross defects were aborted in the early fetal period.

Solar radiation and ultraviolet radiation effects on human health. The effects exerted by CFCs on the stratospheric ozone depletion have been characterized (Cicerone, 1989, 1990). Stratospheric ozone plays an important role in filtering or screening out parts of the UV spectrum. The UV spectrum is illustrated in Figure 2 as a small part of the electromagnetic spectrum. The ultraviolet spectrum is divided into three parts; A, B, and C. The longer wavelengths, UV-A, range from 400 to 320 nanometers. The most biologically active part of the UV spectrum (Figure 3) is the UV-B, 320 to 280 nanometers, which interacts with DNA to form potentially mutagenic events. The UV-B irradiation can induce genetically altered cells or tissues. The third region of the UV spectrum, UV-C, is not known to be biologically active.

Stratospheric ozone is a very effective shield for filtering out ultraviolet (UV) radiation, especially the UV-B component. The resulting destruction and thinning of the stratospheric ozone has increased the amount of radiation entering the earth's troposphere. Table 1 shows the effectiveness of the ozone layer in absorbing components of the UV spectrum. Although UV-B is less than one quarter of the extraterrestrial solar transmission, about 75% of it is filtered out by the stratospheric ozone. Recent estimates (Gleason, et al., 1993) on the global average ozone show a 2-3% decrease in 1992 compared to the previous years measured, 1978-1991. These measurements were derived from the Nimbus 7 satellite carrying a TOMS (Total Ozone Mapping Spectrometer) detection system as well as from ground measurements. Ozone decreases were found to be the largest between 10°S to 20°S and 10°N to 60°N; the equatorial region showed no change. The 1992 measurements were the first to show decreases in such wide latitudes in both the northern and southern hemispheres.

Table 1. Solar radiation spectra before and after passing through atmosphere

Wavelength in nanometers	Watts/m^2		Percent Absorption
	Extraterrestrial solar transmission	Global radiation	
UV-A (400-320)	88	63	28
UV-B (320-280)	22	5	77
UV-C (280-20)	8	0	100

The depletion of ozone is clearly a factor in determining the amount of UV-B passing through the stratosphere. There are several other factors which play important roles on the amount of UV-B measured at the ground level. First, there are differences in stratospheric ozone by geographical regions. There are also seasonal variations of stratospheric ozone which will influence the amount of UV-B absorbed and detected. In the southern hemisphere, the stratospheric ozone levels are lowest in April and May and are highest between mid September and mid November (Stolarski, et al., 1991). In the northern hemisphere between 40°N and 52°N, the total column ozone reductions are about 5% in the winter months and about 2% in the summer months. It has been estimated (Urbach, 1989) that a 1% decrease in stratospheric ozone will result in a 1.25-1.5% increase in UV-B. Ground based measurements of UV-B in the United States between 1975 and 1985 revealed no increased levels of radiation (Scotto, et al., 1988). The absence of detectable increases of UV-B at ground level at a time when stratospheric ozone depletion is present suggests the presence of tropospheric modulators of UV-B radiation. Such modulators include tropospheric ozone, produced by photochemical processes in polluted areas, as well as interaction of UV-B with other tropospheric components such as aerosols, particulates, or clouds.

The continuing depletion of stratospheric ozone accompanied by increasing levels of ultraviolet radiation, specifically UV-B, is expected to increase the incidence of skin cancer, eye diseases, and to impair immune responses in human populations (WHO Task Group, 1990). Evidence is already accumulating to substantiate this prediction. The recent observations of further ozone decreases based on satellite and ground base measurements (Gleason, et al., 1993) increase the likelihood that UV-B levels are already increasing. Unfortunately, systematic UV radiation monitoring has not been developed on a regional or national basis in most parts of the world. Federal agencies of the U.S. government have begun to initiate plans monitoring sites. Monitoring of UV radiation and other environmental and meteorological data are essential for an understanding of the interactions between the radiation and aerosols, particulates, and different types of cloud cover. There is an urgent need for more data to understand the role of the tropospheric modulators of UV to make valid scientific assessments of the UV effects on public health.

Non-melanoma Skin Cancer. Evidence from clinical observations, epidemiologic studies, and experimental data are emerging to establish the understanding of the links between sunlight and skin cancer. There are two basic types of skin cancer, non-melanoma skin cancer (NMSC) and cutaneous malignant melanoma (CMM). Both types of skin cancer are induced by UV-B in combination with other factors. For these cancer types, the incidence is related to genetically determined pigmentation and to the quantity and quality of exposed radiation.

Skin pigmentation is an important factor for protection of solar radiation. Pigmentation in skin is due to the presence of melanin in the epidermis or outer layer of the skin. Melanin is formed by melanocytes, a specialized type of photosensitive cell in the epidermis. The melanocyte responds to sunlight and to UV-B by producing melanin. Melanin plays an important role in prevention of skin cancer because its absorption profile is similar to DNA. Melanin, like ozone, offers protection from UV damage by absorbing and thus blocking harmful radiation from epidermal keratinocyte DNA. Epidermal keratinocytes are the proliferative cells which continually divide and differentiate and provide replacements for those cells normally lost from the surface. The melanocyte population in the epidermis is proportional to the darkness of the skin. Dermatologists classify skin types on a graded scale of I thorough VI, with I being the lightest and VI being the darkest, comparable to American or African blacks or to Australian aborigines (Table 2).

Table 2. Skin types and their general properties

Skin Type	Relative Burn	Relative Tan	Immediate Pigment Darkening (IPD)	Skin Color Description	Group or Region
I	+++++	0	0	Light skin, freckles	Very light Whites
II	+++	0 to +	0 to +	Light pigment	
III	0 to +	+++	+++	Light to medium	
IV	0	+++++	++++	Medium brown, olive to medium brown	American Indian, Mediterranean
V		-	+++++	Brown	Egyptians, Mexicans Malaysians, Puerto Ricans
VI		-	+++++	Black	African or American Blacks, Australian aborigines

Modified from Jones, 1989 and Longstreth, 1989

Non-melanoma skin cancer includes basal cell carcinoma (BCC) and squamous cell carcinoma (SCC). Both of these tumor types are usually superficial and can be surgically removed. The mortality rate for NMSC is less than one percent. It is believed that both of these types of tumors are under estimated because they are not always reported to registries were cancer data is recorded. Data from several sources show that increases in non-melanoma skin cancer is correlated with long term, repeated exposure of solar radiation. The biological action spectrum of UV-B (Fig. 3) suggests that radiation from this range is the primary environmental factor leading to this type of cancer. Therefore, in regions of the world where ozone is being depleted, the problem will intensify. Races with higher levels of pigmentation, or those whose skin responds to sunlight by tanning, are less vulnerable to the disease. Thus, non-melanoma skin cancer is likely to affect people with light colored skin, about 20% of the world's population (WHO Task Group, 1990). Studies on non-melanoma skin cancer in the United States from 1960-86 reveal the incidence of squamous cell carcinoma increased by 260% in men and 310% in women. These increases are higher than that predicted from ozone depletion. Other life style changes, such as excessive sun exposure, are contributing factors. The incidence for both basal and squamous cell carcinomas is higher in the sunbelt regions.

The incidence of BCC is latitude dependent with the highest rates observed in the lower latitudes of the Northern hemisphere. In the Southern hemisphere, the distribution is similar in lower latitude regions. The highest incidences of NMSC in the world are now being observed in Australia (Stenbeck, et al. 1990). The higher incidence in these latter regions is directly related to solar exposure and possibly exacerbated by increasing levels of UV radiation related to the growing depletion of ozone in the southern polar region. BCC incidence increases with age; tumors emerge in chronically sun exposed areas of the head and neck. Outside workers, farmers, and fishermen have the highest incidence of BCC. Approximately half of the patients with xeroderma pigmentosa, a genetic disease characterized by elasticity of the skin and premature skin aging, develop BCC or SCC by the age of 15 (Jones, 1989). No experimental animal models for BCC using UV radiation have been developed. However, the accumulated epidemiological and clinical evidence supports the role of UV radiation in the etiology of this malignancy.

SCC has a distribution pattern similar to BCC. More that 70% of the lesions are on the neck and face. The latitude gradient for the incidence of SCC is similar to that of BCC. Between 1960 and 1986 the age adjusted incidence of NMSC increased from 9.7 to 29.2 in women and from 41.6 to 106.1 in men per 100,000 population, respectively (Longstreth, 1991). UV radiation initiates and promotes SCC in animal models. Thus, there is strong experimental evidence to backup the epidemiological and clinical studies that UV is an important in the etiology of this cutaneous malignancy. For this carcinoma as well as for many others, it is possible that more than one mechanism is responsible for development of the tumor.

A survey of NMSC in the United States was reported in 1978 by Scotto (Longstreth, 1991). At that time it was estimated that between 400,000 and 500,000 new cases of NMSC would develop annually. This represents a 15-20% increase over the levels in 1971. The EPA estimates that a 1% decrease in stratospheric ozone will increase NMSC by 2-3%. At the current birth rate, approximately 260,000,000 cases of NMSC would develop in individuals alive in 1985 or born thereafter up to 2075. Many locations throughout the world do not collect data on NMSC sufficient to relate trend or cohort analyses. Queensland Australia lies between 10°S and 29°S latitude and currently has the highest incidence of NMSC in the world: 1372 for men and 702 for women per 100,000, respectively (Stenbeck, 1990). The incidence also increases with age. The age at which UV exposure occurs appears to be a factor in the etiology of NMSC. Marks and colleagues (Marks, et al., 1990) conducted studies in Australia with natives and English immigrants and found evidence that protection of children from over exposure to solar radiation and UV radiation at an early age reduced the number of NMSC in adulthood. Additional studies in New Zealand (McKenzie, et al.,

1990) reported two readings of UV light at 307 nm at different parts of the day and at different latitudes, 10° latitude apart. The study showed latitudinal differences of 5-10% between two cities at 35°S and 45°S. UV intensity at the wavelengths measured are 13% higher than at comparable northern latitude.

There is evidence that there may be some immune system surveillance for UV-damaged or defective melanocytes SCC. Langerhans cells in the skin perform immune system surveillance. These cells have the ability to identify and to remove melanocytes with carcinogenic potential. Patients, such as organ transplant recipients, who have been treated with immunosuppression drugs or whose immune system have been compromised, show an increased incidence of SCC. UV radiation is also know to cause immune system suppression (Kripke, 1992). These later observations pose some new questions on the relationships and interactions between UV radiation and the immune system in the development of skin cancer.

Malignant Melanoma Skin Cancer. Cutaneous malignant melanoma (CMM) develops from a neoplastic transformation of the pigment producing cells of the epidermis, the melanocyte. Incidence of CMM risk is associated with long exposures to sun light. Studies on incidence show similar patterns to NMSC regarding the latitude gradient and amount of skin pigment. CMM incidence in the U.S. between 1983-89 increased by 87% (Leaf, 1989). In Scotland, recent studies on patients aged 65 and older (McHenry, et al., 1992) showed that the CMM incidence between 1979 and 1989 increased from 12.2/100,000 to 20.7/100,000. In these studies, men had a slightly higher incidence than women. Incidence at ages below age 65 decreases with age to a level in the 20 year old group that is about one quarter of that seen with the more elderly patients. Many tumors occur on the head and neck, but others occur on torso and limbs where minimal exposure to sunlight occurs. The incidence rate of CMM has been increasing more rapidly than the mortality rate . This is attributed to early diagnosis and treatment which leads to a longer survival period.

No experimental animal models for CMM have been developed. However, the clinical evidence supports the idea that the prolonged exposure to UV radiation is closely linked to onset of the disease. Other factors, such as inherited pigmentation, i.e., melanin content of the skin and interaction with the immune system also play an important role in an individual's susceptibility to CMM. The consequences of the thinning of the ozone layer emphasize the importance of gaining a better understanding of the role of all of the above factors in developing skin cancer.

Immune system effects. Some indirect evidence of UV effects on the immune system have been observed by clinicians for many years. For example, UV radiation activates the herpes virus leading to cold sores in the first sunny days of summer. Also, the susceptibility to infectious diseases such as leprosy and leishmaniasis increases after exposure to UV light (Jones, 1989). Experimentally, UV exerts immune system effects (Kripke, et al., 1992). Kripke and co-workers demonstrated these effects by inducing tumors in mice by UV radiation. The induced tumors were isolated and transplanted into genetically similar UV exposed mice and into non-UV exposed mice. The transplanted tumor was rejected by the non-UV exposed mice and grew in the UV exposed mice. These experiments demonstrate an immune system response that will allow the UV-induced tumor to grow in the UV exposed mice but to be rejected in the non-UV exposed mice.

There is a growing body of evidence suggesting immune system suppression associated with UV radiation. Cooper, et al. (1992) have developed bioassay for immune responses after exposure to UV light from the sun or from UV lamps. This bioassay determines the degree of contact sensitivity to DNCB (2,4,-dinitrochlorobenzene). The sensitivity of the immune system to UV has broad implications for the effects of global change on human health. If immune suppression is tightly coupled with UV exposure, the susceptibility to infectious disease could be affected world wide. If immune systems are severely affected, the elderly and those with already compromised immune systems would be most vulnerable. The influence of skin pigment and other compounds such as 'sun blockers' are yet to be determined.

Ocular effects. Since the early 1970s, the incidence of cataracts was associated with tropical and sunny regions. Ultraviolet light exposure has been proposed as a causal factor of cataracts for at least 10 years. Cataracts have an important economic impact on health care since they are causal factors in half of the world's 23 million blind population. Taylor, et al. (1988) studied the watermen of Chesapeake Bay and found a dose response for cortical cataracts and UV-B exposure. The increasing life span will increase the incidence of cataracts in the future. Programs are being developed around the country and the world aimed at reducing or preventing excessive exposure to UV-B. Efforts need to be expanded along these lines to minimize expenses associated with cataracts.

Research approach to investigate the effects of solar radiation on human health

- Establish a monitoring system to accurately characterize the radiation being studied.
- Insure that instrumentation is sufficiently sophisticated to measure parameters most important for human studies.
- Establish a network of monitoring stations to collect data under different environmental conditions.
- Determine what environmental factors (tropospheric compounds which influence solar radiation).
- Determine suitable endpoints and parameters for making measurements for areas being studied.
  - Skin Cancer
  - Ocular effects
  - Immune system effects

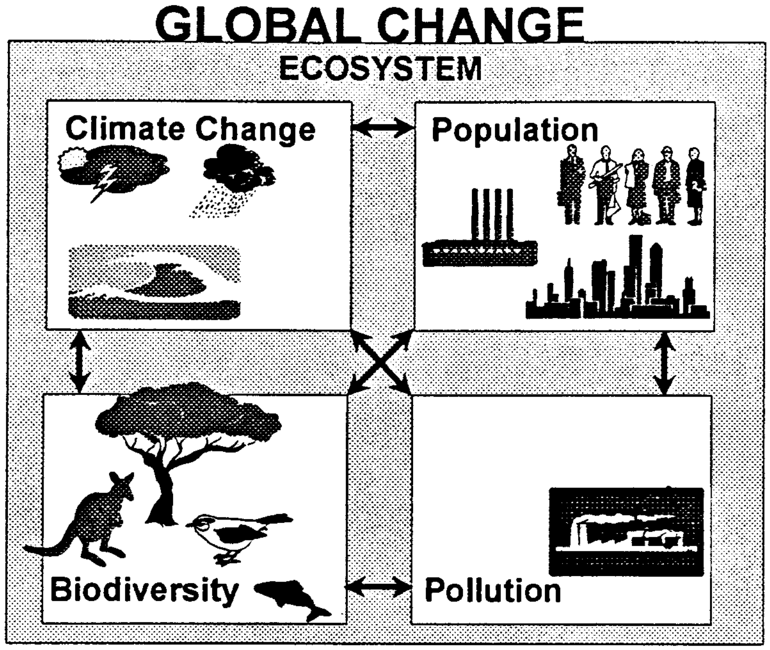

Fig 1A. Interaction of the global change components with the ecosystem.

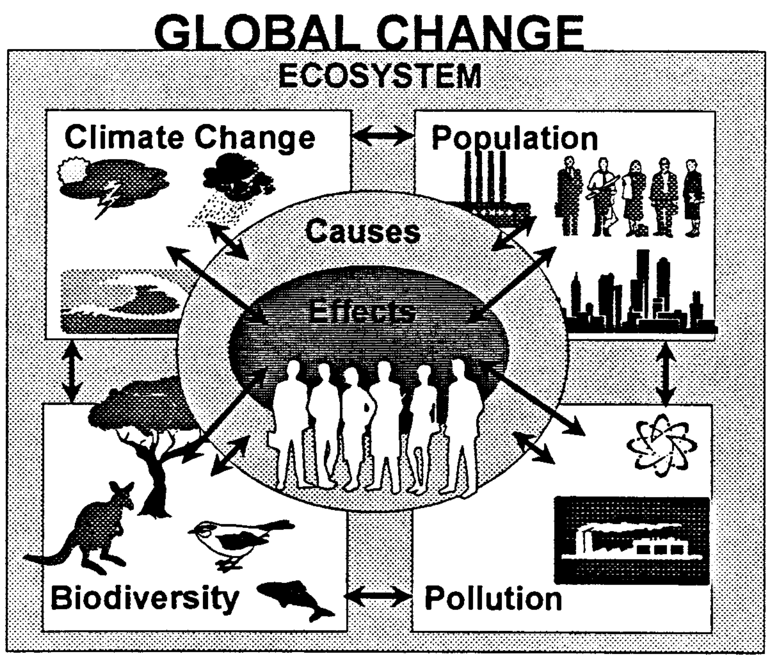

Fig 1B. Human interaction with global change components.

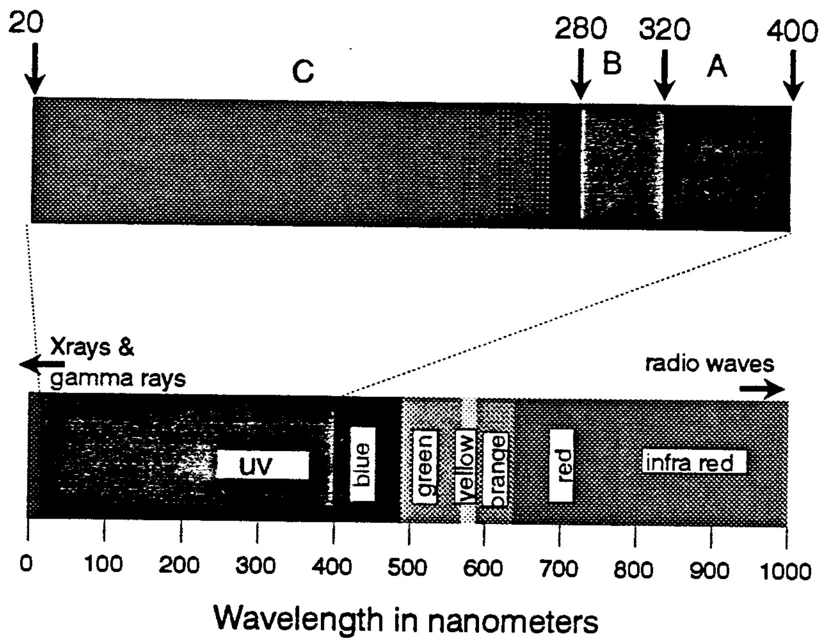

Fig. 2. UV SPECTRUM

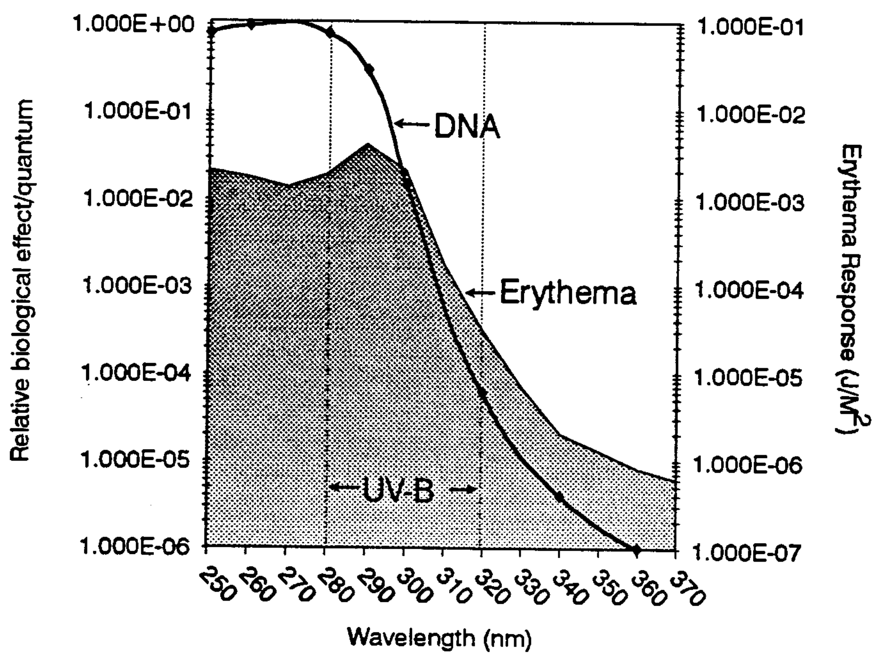

Fig. 3. Relative biological response of DNA and erythremal response to ultraviolet radiation (after Pollard, 1974 and Gange, 1986)

Bibliography

1. Cicerone RJ. Global Warming, Acid Rain, and Ozone Depletion. Abrahamson DE, Editor. The Challenge of Global Warming. Washington, DC: Island Press; 1989. p. 231-238.

2. Cicerone RJ. Greenhouse cooling up high. Nature 1990; 344(6262):104-5.

3. Cooper KD, Oberhalman L, Hamilton TA, Baadsgaard O, Terhune M, LeVee G, Anderson T, Koren H. UV Exposure Reduces Immunization Rates and Promotes Tolerance to Epicutaneous Antigens in Humans: Relationship to Dose, CD1a-DR+ Epidermal Macrophage Induction and Langerhans Cell Depletion. Proc Nat Acad Sci U.S.A 1992;89:8497- 8505

4. Davis RE, Kalkstein LS. Development of an Automated Soatial Synoptic Climatological Classification. Int J Climatol 1990;10: 769-794.

5. Ewan C, Bryant E, Calvert D. Health Implications of Long Term Climate Change, Vol 1, Effects and Responses. Australia: National Health & Medical Research Council, Commonwealth of Australia; 1990. 52 pp.

6. Gentilli J. Some Climatic Factors in Australian Health. Soc Sci & Med 1980;14D:85-100.

7. Gleason JF, Bhartia PK, Herman JR, et al. Record low global ozone in 1992. Science 1993;260:523-526.

8. Haines A. Global warming and health [editorial] [see comments]. BMJ 1991;302(6778):669-70.

9. Jones RR. Consequences for Human Health of Stratospheric Ozone Depletion. Jones RR, Wigley T, Eds. Ozone Depletion: Health and Environmental Consequences. New York: John Wiley & Sons; 1989. p. 207-227.

10. Kalkstein LS. A New Approach to Evaluate the Impact of Climate upon Human Mortality. Environ Hlth Perspectives 1991;96: 145-150.

11. Kalkstein LS, Davis RE. Weather and Human Mortality: An Evaluation of Demographic and Interregional Responses in the United States. Ann Assoc Am Geogr 1989;79:44-69.

12. Kalkstein LS, Tan G, Skindlov JA. An Evalutaion of Three Clustering Procedures for Use in Synoptic Climatological Classification. J Climatol Appl Meteorol 1987;67:717-730.

13. Kripke ML, Munn CG, Jeevan A, Tang JM, Bucana C. Evidence that cutaneous antigen-presenting cells migrate to regional lymph nodes during contact sensitization. J Immunol 1990;145(9):2833-8.

14. Leaf A. Potential health effects of global climatic and environmental changes. N Engl J Med 1989;321(23):1577-83.

15. Longstreth JD, Ed. Ultraviolet Radiation and Melanoma with a Special Focus on Assessing the Risks of Stratospheric Ozone Depletion. Washington: U.S. Environmental Protection Agency; 1989. ((EPA 400/1/001D)).

16. Longstreth JD, de Gruijl FR, Takizawa Y, van der Leun JC. Human Health. Environmental Effects of Ozone Depletion: 1991 Update; 1991. : UNEP; 1991. p. 15-24.

17. Marks R, Jolley D, Lectsas S, Foley P. The Role of Childhood Exposure to Sunlight in the Development of Solar Keratoses and Non-melanocytic Skin Cancer. Med J Aust 1990;152(2):62-6.

18. McCally M, Cassel CK. Medical responsibility and global environmental change [see comments]. Ann Intern Med 1990;113(6): 467-73.

19. McHenry PM, Hole DJ, MacKie RM. Melanoma in People Aged 65 and Over in Scotland, 1979-89. BMJ 1992;304(6829):746-9.

20. McKenzie RL, Elwood JM. Intensity of solar ultraviolet radiation and its implications for skin cancer. N Z Med J 1990; 103(887):152-4.

21. Schwartz J, Hasselblad V, Pitcher H. Air Pollution and Mobididy: A further Analysis of the Los Angeles Student Nurses Data. J Air Pollut Control Assoc 1988;38:158-162.

22. Schwartz J, Moore J, Marcus A. Mortality and Air Pollution in London: A Time Series Analysis. : U.S. Environmental Protection Agency; 1987. Report No.: 1-20.

23. Scotto J, Cotton G, Urbach F, Berger D, Fears T. Biologically effective ultraviolet radiation: surface measurements in the United States, 1974 to 1985. Science 1988;239(4841 Pt 1):762-4.

24. Setlow RB. The Wavelengths in Sunlight Effective in Producing Skin Cancer: A Theoretical Analysis. Proc Nat Acad Sci U.S.A 1974; 71(9):3363-3366.

25. Shore RE. Overview of Radiation-induced Skin Cancer in Humans. Int J Radiat Biol 1990;57(4):809-27.

26. Smith MS, Upfold JB, Edwards MJ, Cawdel-Smith J. The induction of Nerual

Tube Defects by Hyperthermia: A Comparison of the Guinea Pig and Human. Neurobio Appl Neurobiol 1992;18(1):71- 80.

27. Stenbeck KD, Balanda KP, Williams MJ, Ring IT, MacLennan R, Chick JE, Morton AP. Patterns of treated non-melanoma skin cancer in Queensland--the region with the highest incidence rates in the world. Med J Aust 1990;153(9):511-5.

28. Stolarski R, et al. Chapter 2, Ozone and Temperature Trends. Albritton DL, Watson RT. Scientific Assessment of Ozone Depletion: 1991. : World Meterorological Organization: Global Ozone Research and Monitoring Project-Report No. 25, and UNEP, UKDOE, NOAA and NASA; 1991. p. 1-33.

29. Taylor HR, West SK, Rosenthal FS, Munoz B, Newland HS, Abbey H, Emmett EA. Effect of ultraviolet radiation on cataract formation. N Engl J Med 1988;319(22):1429-33.

30. Urbach F. Potential Effects of Altered Solar Ultraviolet Radiation on Human Skin Cancer. Photochem Photobiol 1989;50(4): 507-13.

31. WHO Task Group. **Potential Health Effects of Climatic Change**. Geneva: World Health Organization; 1990. ((WHO/PEP/90/10)).

3.2 ECOSYSTEM AND PUBLIC HEALTH BREAKOUT GROUP PARTICIPANTS

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3.3 BREAKOUT GROUP REPORT

Five-Year Research Plan and Products:

Reports and other modes of communication tailored to the intended audience.

1. Ecosystem and public health cause-effect linkages with climate change; improve understanding of Great Lakes ecosystem structure and function.

2. Indicators and indices of status and trends in Great Lakes ecosystem and public health.

3. Education and communication packages, including development and encouragement of dialogue and feedback.

4. Explore and assess response (management, adaptation, and abatement) strategies.

Education and communication Objectives:

Education and participation is needed for developing a common vision of Great Lakes ecosystem and public health. A Great Lakes constituency is required to build support for the necessary research and understanding of management, adaptation, and abatement alternatives concerning the climate change issue.

Educational initiatives should emphasize the worth of natural resources and the links between ecosystem and public health in the following programs:

- formal education curriculum development (K-12) in interdisciplinary science and social application

- techniques for information transfer and dialogue with stakeholders, resource managers, and politicians

- forum(s) for stakeholders to define and understand desirable/achievable outcomes and actions for themselves

Research on management, adaptation, and abatement alternatives:

- natural area management (habitat preservation) under conditions of climate change.

- habitat and resource restoration and rehabilitation under conditions of climate change.

- impacts and adaptability of land use, with emphasis on cities and managed productive systems (e.g., agriculture and forestry), under conditions of climate change.

Critical Issues:

1. Recognition that there are different perceptions and needs for scientists, resource managers, and politicians focusing on the same issue (climate change). Research designs and packaging of deliverables must be cognizant of these differences, requiring two-way communication from the outset.

2. Recognition of the challenges of interdisciplinary research. A complex issue such as climate change requires a higher degree of collaboration and cooperation than heretofore achieved. Critical problems of linking often disparate data sets with differences in level of detail and scale will be challenging and require data sharing and accessibility.

3. Recognition that research work and decision making will be conducted with uncertainty beyond our normal comfort zone. The need for long term data blurs the distinction between research and monitoring programs.

4. Recognition that education and public awareness should be an integral part, not an afterthought, of building support and understanding of the science, and creating a framework for political, management, and personal action fostering ecosystem and public health.

5. Will the Great Lakes food web respond under climate warming with a compensatory increase in zooplankton and other fish food of the right kind and at the right time to support the hypothesized increased growth and production of fish?

6. What are the interactions between climate change and human health in the Great Lakes region?

7. How do we distinguish climate change effects from other forcings such as non-indigenous species, toxic contamination, over-fishing, over-stocking, and nutrient enrichment? Are there synergistic effects of these forcings?

8. Wetlands, tributaries, and the nearshore zone are poorly understood regions that are nurseries to a variety of fish and wildlife, and are the link between the Great Lakes terrestrial landscape and its point and nonpoint sources of nutrients and contaminants. These habitats may be especially sensitive to climate change and other stresses acting singly or in concert, and their response to change cascades through the entire ecosystem.

Research Objectives:

1. As part of ongoing monitoring programs in the offshore regions of the Great Lakes, increase efforts of process work to understand ecosystem response to physical forcings including:

-stratification
-turbulent water motion at scale of mm to cm
-solar radiation, especially UV
-ice cover
-temperature

Cooperation is needed between biologists and physicists to make sure appropriate physical variables are modeled, predicted and measured. Winter is a critical period that will need special attention because of our lack of knowledge and because of its importance to the cold water fauna. The variables will not only affect rates and amounts but ecosystem structure.

2. Establish UVB monitoring network and relate changes in UVB to human health effects such as skin cancer, cataracts, and immune system dysfunction.

3. Determine possible effects of climate change and its interaction with other global change variables on human health.

4. Establish integrated research and monitoring efforts in wetlands, nearshore, and tributary areas to determine the importance of these areas and their sensitivity to climate change variables.

Research and communication strategy:

Concurrent development of:

1. Assessment of worth. Goals and vision for ecosystem and public health in the basin, including non-use values.

2. Status of the Great Lakes ecosystem.

3. Assessment of the impacts and effects of climate change on ecosystem and public health.

4. Research on management, adaptive, and abatement alternatives.

5. Education and public awareness.

Vision and goals development: Developing a common vision for the Great Lakes ecosystem and public health, including:

1. What is health? What is good for us and the ecosystem to strive for?

2. A suite of environmental endpoints that are agreed upon and measreable.

3. Focus on "wellness" instead of "illness".

4. Emphasize the benefits and values of ecological resources and biodiversity.

4.0 LANDSCAPE/LONG TERM MEASUREMENTS

4.1 ISSUE PAPER

The Role of Paleoenvironmental Studies in Climate Change

by
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Abstract

Planning for global change requires an awareness of what has gone before. If we know the scales, rates, and frequencies of past changes in climate, and how these affect other environmental variables, we can either test or provide boundary conditions for models of future change. Instrumental records are helpful, but they only take us back a few hundred years, at best. A variety of research strategies are available that provide both qualitative and quantitative means of interpreting climates prior to historical time.

Analysis of fossil pollen is the most widely used tool in reconstructing past vegetation and modeling continental climate. Numerous studies are available to relate fossil pollen to modern pollen rain, and modern pollen to climate, and a North American Pollen Database is now available on internet for all to use. Yet problems inherent in pollen analysis have begun to limit the refinement of present research and modeling.

A multidisciplinary approach is needed that would not only supply additional information for refining climate models, but also provide independent tests of current models and incorporate other environmental variables, such as vegetation, soils, and hydrology. This approach involves analysis of larger plant materials, insect, mollusc, vertebrate, and other animal remains, isotopes in cave stalagmites, and changes in the hydrology of streams. Preliminary studies in lowa and adjacent states have resulted in alteration of previous models of past climatic change. They have also added information on changes in these other elements of the environment, which should be incorporated in future models. Such studies should be expanded to include the Great Lakes area.

Introduction

Before we can make meaningful plans to deal with global environmental change, we need to understand the nature of such change. A fundamental source of information about global change is the past. Past changes provide a baseline for evaluating present and future changes, show us the effects of climatic change on other aspects of the environment, and provide boundary conditions for models that attempt to predict future change COMAP Members, 1 988).

Critical issues that relate to climatic change in the Great Lakes and Midwest are:

1. What magnitude of change has occurred in this region over the last 20,000 years? How rapidly has it occurred? Over how large an area?
2. What is the effect of these climatic changes on other aspects of the environment, such as vegetation, soils, or hydrologic cycle?
3. How do these climatic changes compare with historical and potential future climatic changes?
4. How do the climatically-induced changes in vegetation, soils, and hydrology compare with human-induced changes?

This paper briefly reviews some aspects of our current knowledge about the paleoenvironment of the Great Lakes region, how some work in lowa provides a more complete picture of past environmental change, how this information relates to critical issues in global change, and discusses future research needs.

Our approach to studying global change is to use several independent lines of evidence to reconstruct past changes in climate, vegetation, fauna, and landscape evolution. These lines of evidence include plant and animal fossils, changes in stream hydrology and landscape evolution, and geochemical signatures in cave stalagmites. Radiometric dating allows us to establish the times and rates of change.

Present State of Knowledge

Of the several kinds of continental records that yield proxy data for paleoclimatic use, the most commonly used is palynology, the study of fossil pollen grains. Pollen grains are released from plants, deposited in sediment, and preserved. Studies of modern pollen rain show that the pollen deposited represents the surrounding vegetation, which in turn reflects climate. Thus, layer by layer the changes in pollen record changes in vegetation and climate. By assembling pollen sequences from many different sites in a region, we can map regionally important changes in vegetation through time. Modelers, using a variety of statistical techniques, convert pollen data to quantitative estimates of selected climatic variables through time (Bartlein et al., 1984, 1986). These estimates can then be compared with global climate model predictions of past climatic changes (Kutzbach and Webb, 1991). Both model predictions and pollen records can be compared with long, continuous records of other kinds from distant areas (e.g. isotope records from deep-sea sediments and from the Greenland ice core) to evaluate which events are world-wide, continental, regional or local.

The current status of palynological research in the Great Lakes area is that extensive work has been done, and several good summaries of this work exist (e.g. Davis,1983; Webb et al., 1983; Webb, 1988). This work demonstrates that past vegetation and climate can be examined at spatial scales ranging from individual tree stands to entire continents (Graumlich and Davis, 1993; Kutzbach and Webb,1991). Time scales of these records also vary from annual (potentially) to, in the Great Lakes region, the retreat of the last (Wisconsinan) glaciers about 12,000-15,000 years ago. Time resolution is generally hundreds of years, depending on the sample interval and the error bars (often +50 to several hundred years) associated with radiocarbon dating.

Large-scale changes in vegetation are similar throughout the Great Lakes region. As glacial ice retreated, tundra-like environments gave way to sprucedominated forests between about 15,000 and 10,000 years ago, indicating an increase in summer temperature of ~6-7° C. Deciduous and conifer-hardwood forests replaced the spruce about 10,000 years ago, and summer temperatures rose an additional ~2° C. Cooler forest elements advanced southward slightly during the last 3000 years, as summer temperatures approached modern conditions (Davis, 1983; Webb et al., 1983). The maximum shift in temperatures during this time of about 9° C represents the change from glacial to interglacial environments and is the maximum experienced during the last several million years. Precipitation also varies during the last 15,000 years, but changes in the Great Lakes region are generally less than 10 percent. The rates of these changes varied greatly, but the precision is too coarse to estimate changes more rapid than centuries scale. This problem is important because rapid rates of change potentially cause greater environmental disruption, and rates predicted for doubling of CO_2 are very rapid.

Work from annually-laminated sediments improves the resolution of rates of change greatly. Most of the work on these laminated sediments spans only the last 2000 years or less. Clear short-term changes in vegetation are present in these records (e.g. Gajewski; 1988, Swain, 1978), but many may be due to fire and other non-climatic causes. However, short-term climatic changes, such as the "Little Ice Age" cooling, involve shifts of ~0.5° C and last a few centuries, and changes in historical time are of this magnitude or smaller. Changes of larger magnitude have not occurred in the last few centuries.

Pollen analyses of sediments only a few hundred years old have shown that EuroAmerican settlement noticeably affected the region. Ragweed pollen is the **most** sensitive and widespread indicator of post-settlement time; it increases in abundance greatly at the settlement horizon all across the region. Other weedy elements also show increases, indicating that deforestation and cultivation created many disturbed habitats that were colonized by weeds (McAndrews, 1988). Rates of sedimentation in lakes also increased (Maher, 1977). Wetlands also may have changed in character following agricultural activities (Baker, et al., 1987). The specific effect of these changes on the landscape, and the degree that these changes can be recognized from climatic changes is still somewhat unclear from pollen studies alone.

Existing pollen studies in the Great Lakes area have given us a good estimate of the magnitude of climatic change and they show that the entire region was affected by at least the larger changes. They do not handle the problem of potentially rapid changes well, they do not indicate the impact of climatic change on other environmental variables, and their ability to give accurate quantitative climatic estimates is relatively untested. A few studies give some indications on how past change compares to human-induced change. To get a better understanding of these unsolved problems, it is necessary to use a more interdisciplinary approach. The following section describes an example of our work in northeastern Iowa that could be applied to the Great Lakes region.

Recent mulitdisciplinary work

Larger plant fossils (macrofossils: seeds, fruits, leaves, etc.) provide a different picture from pollen analyses; they can be more accurately identified, and they give a more detailed and precise picture of a smaller area. Thus, they represent different aspects of vegetational and climatic changes. Their distribution is more restricted than that of pollen, but pollen is produced in greater numbers and can be more conveniently treated by statistical techniques. These two groups of fossils are often analyzed separately but are most powerful when used together.

Rich macrofossil (and pollen) assemblages are present in many stream cutbanks, where fossils, soils and landscape development can be studied simultaneously. Thus, effects of climatic change can be compared and contrasted with other environmental changes. Dating is more precise, because radiocarbon dates on wood (abundant in stream banks) are less susceptible to dating problems than lake or bog sediments.

Eastern Iowa lies on the northeastern edge of the so-called "Prairie Peninsula," a tongue of prairie which extended into Illinois and Indiana prior to settlement. This expansion is closely tied to the dominance of relatively warm, dry air masses from the west. The prairie was predicted to have expanded between about 9000 and 8000 years ago on the basis of pollen evidence from surrounding regions. Our macrofossil work on these stream-cutbank sites has shown that these models are erroneous both in regional extent of the prairie expansion (by several hundred kilometers), and in the timing of the change (by thousands of years). The prairie did not reach these sites until 5500 years ago, when the forest disappeared very rapidly, perhaps within 100 years or less. Thus a major shift in vegetation occurred, suggesting a very rapid rise in summer temperatures of 1-2° C. Such a shift might be comparable to predicted future changes.

A return of oak forests in response to slightly cooler, moister conditions occurred about 3000 years ago. This change caused a marked change in flooding in nearby southwestern Wisconsin (Knox, 1993). After approximately 3300 years, an abrupt shift in river behavior occurred, with frequent recurrence of so-called 500-year floods (about the size that occurred in Iowa in the summer of 1993). Thus a small shift in climate of ~1-2° C cooler summer temperatures can lead to large hydrological changes in watersheds.

Additional work on pre- and post-settlement changes indicates that land clearance and cultivation caused more changes than any climatic change in the last 10,000 years. Extensive soil erosion in the drainage basin preceded increased flooding, and sediments were deposited to depths of 0.5 to 2 m across the entire floodplain (Baker et al., in press). Changes in the fossil beetle fauna in the sediments indicates that the water quality deteriorated from clear, cold "trout-stream" quality to the present warm, sediment-laden stream shortly after the time of settlement. These human-induced changes in the region are of approximately similar magnitude to those caused by glacial to interglacial climatic changes.

The pre-settlement changes described above have been tested by a completely independent approach, the geochemical analysis of stable isotopes of carbon and oxygen that are present in cave stalagmites. Fractionation of oxygen isotopes depends on the heavy isotope fraction in stalagmite-forming waters and on the temperature at the time of deposition. By selecting the right kind of cave, the temperature record can be closely estimated. Isotopes of carbon depend on the kind of vegetation growing above the site. Plants adapted to warmer, drier conditions have a diff erent pathway for photosynthesis than plants of cool, moist climates. This difference in pathway leads to distinctly different fractions of stable carbon isotopes. Thus prairie plants, for example, produce heavier carbon isotopes than forest plants. These isotopic signatures allow us to test the records from pollen, macrofossils, beetles, and stream behavior by a completely independent measure.

The results of isotopic analysis provide strong support for the eastern Iowa records (Dorale et al.,1993). A sharp drop in oxygen isotope values (indicating a shift towards warmer temperatures) occurs within about 100 years between 6000 and 5500 years ago. This change supports the hypothesis formulated from the vegetational record: a sudden climatic shift, perhaps spanning a few decades, resulted in a very substantial change in vegetation. The carbon isotopes change slowly from ~5500 to 3500 years ago. Although the change in vegetation was swift, a period of almost 2000 years was necessary for the soil detritus and associated carbon isotopes to become equilibrated with the prairie environment. Careful microscopic examination of these stalagmites within the last few months indicates that there is an annual record of change, and that there have been events that match the precipitation and flooding in Iowa during the summer of 1993, exactly as Knox (1993) suggested from the paleohydrologic records.

Future research

Clearly the questions posed at the beginning of this paper are best answered by multidisciplinary studies of past climatic and environmental change. Only by understanding past climatic change and its effect on other environmental variables can we hope to give accurate predictions of future change. Few multidisciplinary efforts of the kind I describe above have been done in the Great Lakes drainage area. Classical pollen studies are available for much of the area, and these provide one measure of the large-scale changes. I propose a research program that would include the following:

1. Additional pollen studies of annually-laminated lakes to provide a record of the frequency and magnitude of short-term change.
2. Multidisciplinary studies on the biota of small stream cutbanks, to provide independent records and greater detail that is lacking in pollen records.
3. Studies of isotopes and annual growth bands in cave stalagmites in all available limestone regions to provide independent checks on the timing, direction, magnitude, and frequency of short-term changes.
4. Modeling studies that would use all the above data to sharpen prediction of both past and future changes in not only climate, but vegetation, soils, landscapes, and human influences.

Items 1-3 above would be key information needed to improve capabilities in Item 4 to predict and manage Great Lakes ecosystems. Such a program could be implemented by expanding NOM, NSF, U.S. Geological Survey, and other funding, and by encouraging interdisciplinary proposals of this nature.

References Cited

Baker, R.G., Horton, D.G., Kim, H.K., Sullivan, A.E., Roosa, D.M., Witinok, P.M., and Pusateri, W.P., 1987, Late Holocene paleoecology of southeastern Iowa: Development of riparian vegetation at Nichols Marsh. Proceedings of the Iowa Academy of Science 94, 51-71.

Baker, R.G., Schwert, D.P., Bettis, E.A. III, and Chumbley, C.A., in press, Impact of EuroAmerican settlement on a riparian landscape in northeast Iowa, midwestern U.S.A: an integrated approach based on historical evidence, floodplain sediments, fossil pollen, plant macrofossils, and insects. The Holocene

Bartlein, P.J., Webb, T. lll, and Fleri, E.,1984, Holocene climatic change in the northern Midwest Pollen-derived estimates. Quaternary Research 22, 361374.

Bartlein, P.J., Prentice, l.C. and Webb, T. lll, 1986, Climatic response surfaces based on pollen from some eastern North America taxa. Journal of Biogeography 13, 35-57.

COMAP Members, 1988, Climatic changes of the last 18,000 years: Observations and model simulations. Science 241, 1043-1052.

Davis, M.B., 1983. Holocene vegetational history of the eastern United States. *In* Late Quaternary of the United States, Volume 2, The Holocene, H.E. Wright, Jr. (ed.), University of Minnesota Press, Minneapolis, p. 166-181.

Dora.le, J.A., Gonzalez, L.A., Reagan, M.K., Pickett, D.A., Murrell, M.T., and Baker, R.G., 1992, A high-resolution record of Holocene climate change in speleothem calcite from Cold Water Cave, Northeast Iowa. Science 258, 1626-1630.

Gajewski, K.,1988, Late Holocene climate changes in eastern North America estimated from pollen data. Quaternary Research 29, 255-262.

Graumlich, L.J. and Davis, M.B. 1993. Holocene variation in spatial scales of vegetation pattern in the upper Great Lakes. Ecology 74, 826-839.

Knox, J.C.,1993, Large increases in flood magnitude in response to modest changes in climate. Nature 361, 430-432.

Kutzbach, J.E. and Webb, T. lll, 1991, Late Quaternary Climatic and vegetational change in eastern North America: Concepts, models, and data, *in* Quaternary Landscapes, L.C.K. Shane and E.J. Cushing, (eds.) University of Minnesota Press, Minneapolis, p. 175-217.

Maher, L.J., Jr.,1977, Palynological Studies in the western arm of Lake Superior. Quaternary Research 7, 14-44.

McAndrews, J.H.,1988, Human disturbance of North American forests and grasslands: The fossil pollen record. *In* Vegetation History, Huntley, B. and Webb, T. lll, (eds.), Dortdrecht, Kluwer, p. 673-697.

Swain, A.M.,1978, Environmental changes during the past 2000 years in northcentral Wisconsin: Analysis of pollen, charcoal, and seeds from varved lake sediments. Quaternary Research 10, 55-68.

Webb, T. lll, Cushing, E.J., and Wright, H.E., Jr.,1983, Holocene changes in the vegetation of the Midwest, *In* Late Quaternary of the United States, Volume 2, The Holocene, H.E. Wright, Jr. (ed.), University of Minnesota Press, Minneapolis, p. 142-165.

4.2 LANDSCAPE/LONGTERM MEASUREMENTS BREAKOUT GROUP PARTICIPANTS

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4.3 BREAKOUT GROUP REPORT

5 Year Research Plan and Products:

1. Initiate integrated long-term studies to reveal the key climate processes and variables that affect the landscape.

2. Initiate studies of long-term lake level histories and ecosystem changes across the landscape and correlate with past climate changes as determined from independent physical data.

3. Conduct a retrospective and prospective study of changes to the landscape from anthropogenic activities in comparison to climate induced factors.

4. Initiate studies to better understand how climate changes alter fluxes and linkages among all major ecosystem compartments (e.g., atmosphere, landscape, water, sub-terrestrial).

Landscape covers all aspects from deep water to upland.

Research Objectives:

1) Determine which climate processes and variables are most important in affecting landscape ecosystems, including biota (anthropogenic vs. natural).

Keys: Climatic variables, most sensitive organisms, most sensitive ecosystems and ecosystem processes, most sensitive economic sectors. Processes of economic adaptation. Look at linkages among compartments.

2) Effects of climate change on hydrologic cycles (ecological and physical).

Keys: seasonality of precipitation, runoff regimes, soil moisture, groundwater levels, atmospheric humidity, extreme events, evapotranspiration.

3) Determine how climate has changed in Great Lakes region over past 10,000 years at various scales and across several parameters.

Keys: Which is more important--secular trends or extreme events...depends on question you are asking. Need to prioritize what is more important.

4) Determine long term water level histories of each lake through sedimentology studies and correlate to past climate changes.

5) Determine changes in ecosystems across the landscape and correlate to past climate changes.

6) Improve the temporal resolution of long-term trends in landscape and climate processes that drive those trends.

7) Improve the understanding of the changing control/linkages among all ecosystem compartments as climate changes.

8) Cumulative effects of terrestrial changes on the Great Lakes.

9) Determine how economic changes associated with climate change might affect land use.

10) Determine how economic sectors and employment are impacted by climate change.

11) Soil moisture.

12) Landform changes with water level declines.

13) The effect of UV-B and greenhouse gases on vegetation.

14) Program of long-term measurements.

15) Adaptive policies.

5.0 PHYSICAL/CLIMATE SYSTEMS

5.1 ISSUE PAPER

Great Lakes Climate Scenarios and Physical Response *

By
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Abstract: Climate change impacts on the Great Lakes may be understood by considering atmospheric scenarios with hydrologic models. Scenarios are traditionally generated as general circulation model (GCM) simulations of the earth's atmosphere. Typically, researchers change historical meteorology to match mean changes observed in the atmospheric scenarios, observe changed process model outputs, and compare to model results from unchanged data. This method keeps spatial and temporal variability the same in the adjusted data sets as in the historical base period. Changes are made independently to each historical meteorological variable, ignoring their interdependencies. GCM simulations are over grids that are coarse compared to the scale of interest of the Great Lakes. Recently, scenarios were taken from other climes and transposed to the Great Lakes to preserve reasonable spatial and temporal variations and to avoid the other problems. In all methods, the linkage between the atmospheric scenarios and the hydrology models allows no feedback between the surface and the atmosphere in scenario development and hydrologic impact estimation. Now, mesoscale atmospheric models are embedded within GCMs and coupled to relevant surface hydrology models. This allows more relevant scales for regional impact estimation and dynamic linkages between the atmosphere and the surface. We must link atmospheric models to existing large-scale irregular-area surface models to adequately portray the hydrology and lake thermodynamics of the Great Lakes. Only as sufficiently fine grids become available for surface hydrology models in the next few years will hydrological impacts be directly estimable from purely gridded models.

Introduction

Climatic change will impact on many aspects of the hydrologic cycle in the Laurentian Great Lakes, with interrelated consequences. The impacts on Great Lakes water supply components and both basin and lake storages and fluxes of water and heat must be understood before these consequences can be assessed. Considerations of situations that may occur (scenarios) help identify possible effects and bound future conditions. Preliminary impact estimates considered simple constant changes in air temperature or precipitation. *Quinn and Croley* (1983) estimated net basin supply to Lakes Superior and Erie. *Cohen* (1986) estimated net basin supply to all Great Lakes. *Quinn* (1988) estimated lower water levels due to decreases in net basin supplies on

Lakes Michigan-Huron, St. Clair, and Erie.[2]

Researchers have run general circulation models (GCMs) of the earth's atmosphere to simulate climates for current conditions and for a doubling of global carbon dioxide levels ($2xCO_2$). They used a larger-than-regional scale for many internally-consistent daily meteorological variables. The U.S. Environmental Protection Agency (*USEPA*, 1984) and *Rind* (personal communication, 1988) used the hydrologic components of general circulation models. They assessed changes in water availability in several regions throughout North America, but the regions were very large. Rind used only four regions for the entire continent and indicated needs for smaller region assessments. Regional hydrological models can link to GCM outputs to assess changes associated with climate change scenarios. *Allsopp and Cohen* (1986) used Goddard Institute of Space Sciences (GISS) $2xCO_2$ climate scenarios with net basin supply estimates.

Other efforts that linked hydrological models to GCM outputs originated in studies commissioned by the U. S. Environmental Protection Agency (EPA). EPA, at the direction of the U.S. Congress, coordinated several regional studies of the potential effects of a $2xCO_2$ atmosphere. The studies addressed various aspects of society, including agriculture, forestry, and water resources (*USEPA*, 1989). They directed others to consider alternate climate scenarios by changing historical meteorology similar to the changes observed in GCM simulations of $2xCO_2$, observing changed process model outputs, and comparing to model results from unchanged data. *Cohen* (1990, 1991) discusses other studies that use this type of linkage methodology and also discusses his concerns for comparability between studies using different types.

As part of the EPA study, the Great Lakes Environmental Research Laboratory (GLERL) assessed steady-state and transient changes in Great Lakes hydrology consequent with simulated $2xCO_2$ atmospheric scenarios from three GCMs (*Croley*, 1990; *Hartmann*, 1990; *USEPA*, 1989). Those studies, in part, and the high water levels of the late 1980s prompted the International Joint Commission (IJC) to reassess climate change impacts on Great Lakes hydrology and lake thermal structure. GLERL adapted the EPA study methodology for the IJC studies (*Croley*, 1992b) to consider $2xCO_2$ GCM scenarios supplied by the Canadian Climate Centre (CCC).

This paper outlines GLERL's physical process models, presents the methodology of linkage between regional hydrological models and GCMs, interprets problems with the methodology, and outlines directions for future climate change assessment methodologies.

Great Lakes Physical Process Models

GLERL developed, calibrated, and verified conceptual model-based techniques for simulating hydrological processes in the Laurentian Great Lakes (including Georgian Bay and Lake St.Clair, both as separate entities). These include models for rainfall-runoff [121 daily watershed models (*Croley*, 1983a,b; *Croley and Hartmann*, 1984)], over-lake precipitation (a daily estimation model), one-dimensional (depth) lake thermodynamics [7 daily models for lake surface flux, thermal structure, and heat storage (*Croley*, 1989, 1992a; *Croley and Assel*, 1993)], channel routing [4 daily

[2]GLERL contr. # 879

models for connecting channel flow and level, outlet works, and lake levels (*Hartmann*, 1987, 1988; *Quinn*, 1978)], lake regulation [a monthly plan balancing Lakes Superior, Michigan, and Huron (*International Lake Superior Board of Control*, 1981, 1982) and a quarter-monthly plan regulating Lake Ontario and the St. Lawrence Seaway outflows (*International St. Lawrence River Board of Control*, 1963)], and diversions and consumptions (*International Great Lakes Diversions and Consumptive Uses Study Board*, 1981).

The GLERL Large basin Runoff Model uses daily precipitation, minimum and maximum air temperature, and insolation to determine daily moisture storages, evapotranspiration, and basin runoff for each of the 121 watersheds contributing runoff to the Great Lakes. The model uses meteorological data from over 1800 stations about and in the watersheds, combined through Thiessen weighting. The GLERL Lake Evaporation and Thermodynamics Model of lake heat storage and surface fluxes uses daily air temperature, dewpoint temperature, wind speed, and cloud cover to determine lake heat fluxes and storage, surface temperature, and evaporation. It uses daily meteorological over-land data from 5 to 10 near-shore stations about each Great Lake, assembled and averaged by way of Thiessen weights, for correction to over-lake data. GLERL assembled daily historical data as areal averages for all 121 watersheds (precipitation and minimum and maximum air temperatures) for all periods used in their climate change studies. They also assembled daily historical data as areal averages for all seven lakes (precipitation, air temperature, dewpoint temperature, wind speed, and cloud cover) for the same periods.

EPA Methodology

GLERL integrated the models into a system to estimate lake levels, whole-lake heat storage, and water and energy balances for forecasts and for assessment of impacts associated with climate change (*Croley*, 1990, 1992b; *Croley and Hartmann*, 1987; *Croley and Lee*, 1993). GLERL developed the system specifically to look at the impact of changed climate by doing simulations with changed meteorology (that represent scenarios of changed climate) and comparing with simulations based on historical meteorology (representing an unchanged climate).

Steady-State Climate Change Assessments. EPA required that GLERL first simulate 30 years of "present" Great Lakes hydrology by using historical daily average, maximum, and minimum air temperatures, precipitation, wind speed, dewpoint temperature, and cloud cover data for the period 1 January 1951 through 31 December 1980 with present diversions and channel conditions. They called this the "base case" scenario. GLERL arbitrarily set the initial conditions but used an initialization simulation period of 1 January 1948 through 31 December 1950. This allowed the models to converge to conditions (basin moisture storages, lake heat storages, water surface temperatures, and lake levels) initial to the period of 1 January 1951 through 31 December 1980. GLERL repeated this 30-year simulation, with initial conditions set equal to their averages over the simulation period, until these averages were unchanging. This facilitated investigation of "steady-state" conditions. The next step was to conduct simulations with adjusted data sets.

EPA obtained output from atmospheric GCM simulations, representing both "present" and $2xCO_2$ steady-state conditions, from GISS, the Geophysical Fluid Dynamics Laboratory (GFDL), and the Oregon State University (OSU). They then supplied ratios of $2xCO_2$ to present monthly absolute air temperature, specific humidity, cloud cover, and precipitation, and differences of $2xCO_2$ and present wind speed to GLERL every 7.83° latitude by 10° longitude (GISS), 4.44° by 7.5° (GFDL), and 4° by 5° (OSU). GLERL applied these monthly adjustments to their daily historical data sets to estimate 33-year sequences of atmospheric conditions associated with the $2xCO_2$ scenarios. They inspected each of the 770,000 square kilometers within the Great Lakes basin to see which of the GCM grid points were closest for each GCM (GISS, GFDL, and OSU). Then they applied the monthly adjustment at that grid point to the square kilometer. By combining these values for all square kilometers representing a watershed or a lake surface, they derived areally-averaged monthly scenario adjustments which they applied to their areally-averaged daily historical data sets for the watershed or lake surface, respectively, to derive the $2xCO_2$ meteorology scenario (they used each monthly adjustment for all days of the month). This method keeps spatial and temporal (inter-annual, seasonal, and daily) variability the same in the adjusted data sets as in the historical base period.

GLERL then used the $2xCO_2$ scenario in hydrology impact model simulations similar to those for the base case scenario. As for the base case scenario, they repeated the simulation until long-term averages, also used as initial conditions, were unchanging in an attempt to address steady-state conditions. They interpreted differences between the $2xCO_2$ scenario and the base case scenario as resulting from the changed climate.

Transient-Case Climate Change Assessments. EPA obtained several more GCM simulations to represent the interim from the present to future $2xCO_2$ conditions. As instructed by EPA, GLERL first simulated 80 years of "present" lake levels and component processes over the period 1981-2060 by using historical daily data for the 1951-80 period, repeated three times. The first simulation used initial conditions observed 1 January 1981. The second used the end-of-run conditions from the first simulation as initial conditions and the third used end-of-run conditions from the second. After completing this "base case" scenario, they conducted simulations with adjusted data sets.

EPA supplied 9 sets of monthly $2xCO_2$ adjustments, one set for each decade from 1970-79 through 2050-59. GLERL interpolated between decadal averages to obtain adjustments for each month of each year of the period 1981-2059. They applied them in three simulations as for the base case. They made the 1981-2010 adjustments to the 1951-80 data for the 1981-2010 period simulation. They made the 2011-40 adjustments to the 1951-80 data for the 2011-40 simulation. They made the 2041-59 adjustments to the 1951-1969 data for the 2041-59 simulation. They took the 2060 adjustment the same as the 2059 adjustment, since the GISS scenario ended in 2059, and applied it to 1970 data for the 2060 simulation. GLERL again combined adjustments for each month from the nearest atmospheric model grid point for all square kilometers representing a watershed or a lake surface to derive an areally-averaged adjustment for each watershed or lake surface. They then used the transient scenario segments in simulations as they did with the original historical data. They combined them to represent the entire period of interest and then interpreted differences between the $2xCO_2$ transient scenario and the base case scenario as resulting from the changing climate.

In simulating 80 years (1981-2060) by using 30 years of historical data (1951-80) repeated three times, the variations contained in the historical record repeat of course. GLERL found that the repeating fluctuations of the historical record completely dominated the superimposed climate changes, obscuring climate change effects. GLERL discerned the $2xCO_2$ signal from the historical variations by comparing values 30 years apart, thus eliminating the (repetitive) historical variations. They compared $2xCO_2$ and base case simulation changes for decades 1, 4, and 7 (1981-90, 2011-20, and 2041-50, each based on the same 1951-60 data period). Likewise, they compared changes for decades 2, 5, and 8 (1991-00, 2021-30, and 2051-60, each based on the same 1961-70 data period). Finally, they compared changes for decades 3 and 6 (2001-10 and 2031-40, each based on the same 1971-80 data period).

IJC Methodology

GLERL's general procedure for the investigation of steady-state behavior under a changed climate for the IJC is similar to that used for the EPA, as detailed above and elsewhere (*Croley*, 1992b) except that the period 1948-88 was used for the simulations. GLERL also modified their procedure to estimate "steady-state" conditions, which formerly was to repeat the simulation with initial conditions set equal to their averages over the simulation period, until they were unchanging. This procedure required many iterations for a few subbasins with very slow groundwater storages and suggested very different initial groundwater storages than were used in calibrations. Actually, the original calibrations of the models used arbitrary (but fixed) initial conditions. GLERL should have determined initial conditions also in the calibrations, but that was unfeasible; there is little confidence in calibrated parameter sets that suggest very slow groundwater storages (half-lives on the order of several hundred years in some cases) since only 10 to 20 years were used in the calibrations. Therefore, the best present hydrology estimates are initial conditions on the same order as those assumed for the calibrations for those few subbasins.

Average monthly meteorological outputs were supplied for each month of the year by the CCC as resulting from their second-generation GCM; see *McFarlane* (1991). While available every 3.75° latitude by 3.75° longitude, *Louie* (1991) interpolated monthly averaged data to 1° latitude by 1° longitude by weighting original values inversely to the square of their distance from each new location. GLERL computed $2xCO_2$ monthly adjustments at each location, used them with historical data to estimate the $2xCO_2$ 41-year sequences (1948-88) for each Great Lake basin, and then used the $2xCO_2$ scenario in simulations similar to the base case as before.

GCM Linkage Problems

The hydrological study results from the EPA and IJC studies should be received with caution as they are, of course, dependent on the GCM outputs with inherent large uncertainties in the GCM components, assumptions, and data. Transfer of information between the GCMs and GLERL's hydrologic models in the manners described above involves several assumptions. Solar insolation at the top of and through the atmosphere on a clear day are assumed to be unchanged under the changed climate, modified only by cloud cover changes. Over-water corrections are made in the same way, albeit with changed meteorology, which presumes that over-water/over-land atmospheric relationships are unchanged.

Heat budget data from GCM simulations for Great Lakes grid points may not adequately describe conditions over the lakes due to the coarse resolution of the grids. GLERL's procedure for transferring information from the GCM grid is an objective approach but simple in concept. It ignores interdependencies in the various meteorologic variables as all are averaged in the same manner. Of secondary importance, the spatial averaging of meteorologic values over a box centered on the GCM grid point (implicit in the use of the nearest grid point to each square kilometer of interest) filters all variability that exist in the GCM output over that box. If GCM output were interpolated between these point values, then at least some of the spatial variability might be preserved. The interpolation performed by *Louie* (1991) from the original GCM grid to a finer grid reduced this problem, but it still exists in the use of the finer grid with the hydrology models. Of course, little is known about the validity of various spatial interpolation schemes and, for highly variable spatial data, they may be inappropriate. Furthermore, much of the variability at the smallest resolvable scale of GCMs is, unfortunately, spurious.

Spatial and temporal variabilities of the base case and $2xCO_2$ data sets are the same in the EPA and IJC studies. The methodology does not address changes in variabilities that would take place under a changed climate. The method of coupling used herein does not reproduce seasonal timing differences under a changed climate from the GCMs but preserves seasonal meteorological patterns as they exist in the historical data. This is a result of applying simple ratios or differences to calculate one from the other. This implicitly ignores spatial and temporal phase and frequency changes consequent in the $2xCO_2$ GCM simulations. For example, a changed climate alters the movement (direction, speed, frequencies) of air masses over the lakes. This implies an alteration of the seasonal temporal structure for storms and cyclonic events as well as the intensities of storms. The above method only allows modification of the latter. Seasonal changes induced by the changed meteorology because of a time-lag storage effect are observable, however. Shifts in snowpack or in the growth and decay of water surface temperatures are examples. Changes in annual variability are less clear, again as a result of using the same historical time structure for both the base case and the changed climate scenarios.

MCC Methodology

While the EPA and IJC studies looked at changes in the mean values of hydrologic variables, changes in ***variability*** were unaddressed. This variability is the singular key problem for shipping, power production, and resource managers. GLERL and the Midwest Climate Center (MCC) now are investigating the effects of shifts in the daily, seasonal, inter annual, and multi-year climate variability on lake net supply behavior, as well as related changes in mean supplies. They are doing this by utilizing data for climates which actually exist and that resemble some of the $2xCO_2$ GCM scenarios. These are located to the south and west of the Great Lakes. Lengthy (at least 40 years) and detailed records of daily weather conditions at about 2000 sites are available to represent physically plausible and coherent scenarios of alternate climates. Such data sets incorporate reasonable values and frequencies of extreme events, ensuring that the desired temporal and spatial variabilities are represented, and are being transposed over the Great Lakes.

MCC supplied the data and GLERL transposed them to the Great Lakes by relocating all meteorologic station data and Thiessen-weighting to obtain areal averages over the 121 watersheds and 7 lake surfaces for all days of record (1948-1992). GLERL also reduced all historical data (base case) within the Great Lakes (1900-1990). This involved extensive error checking and data correction for thousands of stations, and regeneration of areal averages. Since the Great Lakes affect the climate near the shoreline but these effects are not present in the transposed data sets, MCC prepared maps of generalized seasonal lake effects on the area's meteorology, to be applied to the transposed climates.

The Great Lakes hydrology of each transposed climate is estimated, as before, by applying the system of hydrological models to these data sets directly and comparing outputs for each transposed climate to a base case derived with the models from historical meteorological data.

Coupled Hydrologic and Atmospheric Research Model (CHARM)

The linkage between GCM and hydrology models allows no feedbacks between these independent models. This is also true with the use of transposed climates. That is, the hydrology does not interact with the transposed climates, other than through use of the estimated lake-effect maps derived under the present climate. While the GCMs have crude hydrologic process models, they represent inappropriately large scales and use very simplified conceptualizations. The regional hydrologic impact models may do a much better job of representing the hydrology of an area. However, their use with GCM outputs does not allow the GCM simulations to benefit from these refined processes. The feedback from the land and lake surfaces' hydrometeorological properties cannot exist without incorporating the regional hydrology models into the atmospheric models.

Modelers are turning their attention to mesoscale atmospheric models to enable better assessment of local to regional effects. The leading approach now is to embed mesoscale atmospheric models within GCMs for a region of interest and to couple relevant surface hydrology models to the mesoscale atmospheric model (*Dickinson et al.*, 1989; *Giorgi*, 1990; *Hostetler et al.*, 1993). This allows both the use of more relevant scales for regional impact estimation and the consideration of dynamic linkages between the atmosphere and the surface, now recognized as essential in describing the hydrology and meteorology of an area. This approach has generally been limited in the past to 50-km grids or larger because of the complexity of the modeling system that is required and because of the computer power that was required. The science panel of the GEWEX Continental-Scale International Project and the WMO-CAS Working Group on Numerical Experimentation launched their joint Project for Intercomparison of Land-Surface Parameterization Schemes (PILPS). The National Center for Atmospheric Research (NCAR) is currently exploring the possibility of operating their atmospheric, hydrologic, and lake flux models embedded in their GCM at scales finer than 50 km.

To estimate impacts associated with both large and fine scales of parameter changes, the Great Lakes research community can address these scales separately. This offers the advantage that we can begin *now* to look at large-scale parameter changes (such as lake levels, lake-wide heat storage, and annual and monthly water and energy balances) by combining *existing* process models appropriate to these scales. This can be underway while fine-scale parameter changes are investigated. They will require more development and integration of process models. Thus, we have two components to physical modeling of climate-change impacts over the Great Lakes. The first is the integration and use of existing Great Lakes hydrologic process models (lumped-parameter, applying to irregular-shaped areas over spatial scales of 30-100 km for the land surface and 100-300 km for the lake surface and temporal scales of 10-100 days). The second is the development and integration of fine-scale second-generation (gridded) surface hydrologic process models (at scales from 1 km to 30 km) with atmospheric mesoscale models.

Large-Scale Parameter Changes. We must explore linkages to atmospheric models for existing large-scale irregular-area surface models that already represent excellent portrayals of the hydrology and lake thermodynamics in the Great Lakes. Since hydrological models exist now for large-scale parameter change estimates, large-scale couplings will be useful in beginning derivative studies (such as socio-economic, food-web dynamics, and other secondary impacts identified as dependent on large-scale parameter changes). They will also prove useful as a starting point for subsequent second-generation joint atmospheric-hydrological parameterizations and in the verification of same and of like developments by other investigators. They will also be useful as a base-line for comparing multiple approaches in modeling the atmosphere and hydrology.

GLERL, in cooperation with the Air Resources Laboratory (ARL), is now linking their hydrology models with the Regional Atmospheric Modeling System or "RAMS" (*Pielke*, 1990; *Lyons et al.*, 1990, 1991a,b). The combination will be used for large-scale parameter investigations, requiring assessment of the temporal and spatial incompatibilities that exist between mesoscale meteorological and regional hydrology models. A modest target is to arrange for coupled modeling by using a 40-km grid, with time steps of 90 seconds in the atmospheric component, coupled to some components of the surface models defined over irregular areas on 12- to 24-hour intervals. RAMS-predicted atmospheric momentum, temperature, moisture, and precipitation fields will be input to the large-scale hydrological models which will use these fields to update sea surface temperature, soil moisture, and snowpack variables. These hydrological parameters will then be input into RAMS to drive the surface energy fluxes over both land and water.

Large-Scale Model Couplings. Since there is some overlap in function between parts of the atmospheric model and the surface models, decisions are required about which model should be used for some purposes. The Large Basin Runoff Model was modified to use potential evapotranspiration calculated by the Richardson number-dependent mixing length method of Quinn (1979) and will be recalibrated as part of CHARM. A Richardson number-dependent scheme for evaporative and sensible heat fluxes (Quinn, 1979) was included in RAMS for consistency with the Lake

Evaporation and Thermodynamic Model.

Most approaches for coupling define land surface parameterizations spatially over a surface grid that matches that used by the mesoscale model. This offers the advantage of direct coupling of relevant fluxes between the atmosphere and the surface. However, it introduces problems in the representation of surface hydrology that does not bear directly on the atmospheric modeling. For example, surface runoff models, defined over the hydrological basin or watershed, offer much better representation of runoff than do spatial models that represent the hydrology at grid points.

GLERL is able to determine how much of each grid box overlaps with each sub-basin for the Large Basin Runoff Model and each lake for the Lake Evaporation and Thermodynamics Model. GLERL gets a weighted average over each grid box of the parameters related to the upper and lower soil zones. By using these parameters, GLERL solves for the snowpack, snowmelt, upper and lower soil zone storage, runoff, percolation, interflow, and deep percolation at each of the grid boxes. This calculation is made at every atmospheric timestep because the snowpack and upper and lower soil zone storages are considered to be directly interactive with the atmosphere.

Since the groundwater and surface storage do not interact directly with the atmosphere, their prediction is done separately at longer time intervals, and is represented on the basis of the irregular sub-basin areas rather than the artificial grid of the atmospheric model. At 12-hour intervals, the fluxes into the groundwater and surface storage reservoirs are combined from the grid over each sub-basin by using weights complementary to those just mentioned (i.e., the fraction of the subbasin in each grid cell); the groundwater outflow and stream flow and updated groundwater and surface storages then are calculated for each sub-basin.

Likewise, the fluxes of shortwave and longwave radiation and latent and sensible heat into the lake surfaces are calculated at each grid point at each timestep. The total heat flux and wind speed for 24 hours are then combined from the grid over each entire lake. The total heat storage in the lake and the lake surface temperature are then calculated. A 24-hour timestep is necessary for the Lake Evaporation and Thermodynamic Model, as it was calibrated using this timestep, and thus ignored diurnal variations in the net heat flux. Work is in progress to modify the LETM to make it synchronous (i.e. lake surface temperature will respond immediately to surface heat flux) and more appropriate for diurnally varying forcing.

Second-Generation Fine-Scale Atmospheric-Hydrologic Integrations. Only when sufficiently fine grids become available for surface hydrology models will surface runoff at points into the lakes be directly estimable from purely gridded models. These fine grids will be approached in the next few years. Likewise, lake heat storage models for the Great Lakes exist at several levels, from one-dimensional superposition models to three-dimensional circulation models. Again, researchers are approaching fine grids that are usable in long continuous simulations.

Two fine-scale approaches are possible now. The first uses developing atmospheric-hydrologic mesoscale models to estimate joint meteorology and hydrology for surface areas of interest in the Great Lakes and then refines the hydrological estimates through use of the better-calibrated GLERL hydrology models for the Great Lakes. This approach is similar to that taken in linking hydrology models to GCM outputs, described previously. Again, there is no dynamic interaction between the final hydrology models and the atmospheric model. Outputs from the joint atmospheric-hydrologic mesoscale model are inputs to the hydrology models. However, better agreement should be possible since the scales of both sets of models are closer than was true in the GCM-hydrology model studies. NCAR has asked GLERL to use their joint atmospheric-hydrologic mesoscale model outputs for the Great Lakes in this manner to study climate change impacts.

The second fine-scale approach consists of developing second-generation fine-scale Great Lake hydrologic and lake thermodynamic models on finer grids to interface directly with atmospheric models applied at ever-finer resolution and of assessing the importance of two-way runoff-atmospheric interactions unique to CHARM. These will complement similar efforts elsewhere (NCAR) that use alternate models. The matching of spatial and temporal scales between models will proceed at different levels. Linkage will begin with coarse irregular spatial and temporal scales, where existing hydrological models are established over large areas in the Great Lakes (as in the above section), and proceed to finer scales as hydrological models are redeveloped in atmospheric-hydrologic studies. Comparisons will be made between scales to see what is resolved and what process refinements make no difference with regard to different uses (water level estimation, sea breeze predictions, and so forth). Both the atmospheric and hydrological models will be run in three dimensions on the same grid. The grid spacings will be reduced from 30 km to 15, 10, 5, and 1 km scales. For the smaller scales, non-hydrostatic physics and explicit cloud microphysics will be employed. To start out, interactions will be performed at the time step of the atmospheric model (between 5-90 seconds depending on the horizontal resolution of the grids). Sensitivity experiments will be performed to determine an optimum update frequency between the atmospheric and hydrologic models since it may not be necessary to interact the models every time step.

Summary

Earlier assessments used atmospheric GCM outputs as meteorologic scenarios to drive process models for generating hydrologic scenarios. Climate change effects were inferred by comparing process model outputs for a base case with the changed climate scenario. As the linkage methods of these assessments constrained spatial and temporal meteorologic variabilities to those present in the historical records, impact assessments began with the transferrence of existing climates to the Great Lakes. ***Meteorologic scenarios (from CCC GCM outputs and MCC transposed climates) and the associated hydrologic scenarios (from GLERL's hydrologic process models) are available for current studies of secondary impacts in the Great Lakes.*** Lack of feedback between surface process models and atmospheric models is still a problem.

Researchers are now developing and verifying multi-scale hydrologic models, with appropriate links to mesoscale atmospheric models, using spatially extensive observations based upon satellite and in-situ measurements and supported by field experiments. These linked models are slated to be embedded in GCM or other boundary condition simulations to assess climate change effects. GLERL is working with ARL to investigate alternative CHARM possibilities. Now underway are a large-scale coupling, that employs GLERL's existing irregular-area surface models, and a series of finer-scale couplings where surface models are defined over the same (surface) grid as used in the mesoscale atmospheric models. GLERL also plans to work with existing and developing coupled atmospheric-hydrologic mesoscale models over the Great Lakes by refining hydrologic estimates with more-detailed hydrologic and lake surface flux models.

References

Allsopp, T. R., and S. J. Cohen, 1986. CO_2-Induced climate change and its potential impact on the Province of Ontario. In: *Preprint Volume, Conference on Climate and Water Management - A Critical Era*, American Meteorological Society, Boston, Massachusetts, 285-290.

Cohen, S. J., 1986. Impacts of CO_2-induced climatic change on water resources in the Great Lakes basin." *Climatic Change*, **8**:135-153.

Cohen, S. J., 1990. Methodological issues in regional impacts research. In: *Proceedings of an International Symposium/Workshop on Climate Change, Implications for Water and Ecological Resources*, G. Wall and M. Sanderson (eds.), Department of Geography Publication Series, Occasional Paper No. 11, University of Waterloo, Waterloo, Ontario, 31-43.

Cohen, S. J., 1991. Caveats in applying GCM output to regional impact assessments. *Proceedings of A Symposium on Climate Scenarios*, The Water Network, University of Waterloo, Waterloo, 16-32.

Croley, T. E., II, 1983a. Great Lakes basins (U.S.A.-Canada) runoff modeling. *Journal of Hydrology*, **64**:135-158.

Croley, T. E., II, 1983b. Lake Ontario basin (U.S.A.-Canada) runoff modeling. *Journal of Hydrology*, **66**:101-121.

Croley, T. E., II, 1989. Verifiable evaporation modeling on the Laurentian Great Lakes. *Water Resources Research*, **25**(5):781-792.

Croley, T. E., II, 1990. Laurentian Great Lakes double-CO_2 climate change hydrological impacts. *Climatic Change*, **17**:27-47.

Croley, T. E., II, 1992a. Long-term heat storage in the Great Lakes. *Water Resources Research*, **28**(1):69-81.

Croley, T. E., II, 1992b. Climate change impacts on Great Lakes water supplies. *Proceedings of the Symposium on Managing Water Resources During Global Change*, Twenty-Eighth American Water Resources Association Conference, 241-250.

Croley, T. E., II, and R. A. Assel, 1993. A one-dimensional ice thermodynamics model for the Laurentian Great Lakes. *Water Resources Research*, (in press).

Croley, T. E., II, and H. C. Hartmann, 1984. Lake Superior basin runoff modeling. *NOAA Technical Memorandum ERL GLERL-50*, National Technical Information Service, Springfield, Virginia.

Croley, T. E., II, and H. C. Hartmann, 1987. Near real-time forecasting of large lake supplies. *Journal of the Water Resources Planning and Management Division*, ASCE, **113**(6):810-823.

Croley, T. E., II, and D. H. Lee, 1993. Evaluation of Great Lakes net basin supply forecasts. *Water Resources Bulletin*, **29**(2):267-282.

DeCooke, B. G., and D. F. Witherspoon, 1981. Terrestrial water balance. In *IFYGL - The International Field Year for the Great Lakes*, E. J. Aubert and T. L. Richards (eds.), Great Lakes Environmental Research Laboratory, Ann Arbor, 210-219.

Dickinson, R. E., R. M. Errico, F. Giorgi, and G. T. Bates, 1989. A regional climate model for the western United States. *Climatic Change*, **15**:383-422.

Giorgi, F., 1990. On the simulation of regional climate using a limited area model nested in a general circulation model. *J. Climate*, **3**:941-963.

Hartmann, H. C., 1987. An evaluation of Great Lakes hydraulic routing models. *NOAA Technical Memorandum ERL GLERL-66*, Great Lakes Environmental Research Laboratory, Ann Arbor.

Hartmann, H. C., 1988. Historical basis for limit on Lake Superior water level regulations. *Journal of Great Lakes Research*, **14**(3):316-324.

Hartmann, H. C., 1990. Climate change impacts on Laurentian Great Lakes levels. *Climatic Change*, **17**:49-67.

Hostetler, S. W., G. J. Bates, and F. Giorgi, 1993. Interactive coupling of a lake thermal model with a regional climate model. *J. Geophys. Res.*, **98**:5045-5057.

International Great Lakes Diversions and Consumptives Uses Study Board, 1981. *Great Lakes Diversions and Consumptive Uses*. International Joint Commission, Washington, D. C.

International Lake Superior Board of Control, 1981. *Regulation of Lake Superior: Plan 1977 Development, Description, and Testing*. International Joint Commission, Washington, D. C.

International Lake Superior Board of Control, 1982. *Regulation of Lake Superior: Operational Guides for Plan 1977*. International Joint Commission, Washington, D. C.

International St. Lawrence River Board of Control, 1963. *Regulation of Lake Ontario: Plan 1958-D*. International Joint Commission, Washington, D. C.

Louie, P. Y. T., 1991. Proposed GCM scenarios for the phase 2 study. *Proceedings of A Symposium on Climate Scenarios*, The Water Network, University of Waterloo, Waterloo, 67-78.

Lyons, W. A., and R. A. Pielke, 1990. Predicting 3-D wind flows at Cape Canaveral Air Force Station using a mesoscale numerical model. Final Report NASA SBIR Phase I, 325 pp.

Lyons, W. A., R. A. Pielke, W. R. Cotton, C. S. Keen, D. A. Moon, and N. R. Lincoln, 1991a. Some considerations of the role of the land/lake breezes in causing elevated ozone levels in the southern Lake Michigan region. *Environmental Modeling*. P. Melli and P. Zannetti, Editors. Computational Mechanics Publications, Elsevier Applied Science, pp. 151-170.

Lyons, W. A., C. S. Keen, R. A. Pielke, W. R. Cotton, D. A. Moon, and N. R. Lincoln, 1991b. A prototype real-time forecasting system for mesoscale dispersion in land/lake breezes. *Proc. Third Topical Meeting on Emergency Preparedness and Response*. Chicago, Illinois, pp. 99-102.

McFarlane, N. A., 1991. The Canadian Climate Centre second-generation global circulation model. *Proceedings of A Symposium on Climate Scenarios*, The Water Network, University of Waterloo, Waterloo, 3-15.

Pielke, R. A., W. A. Lyons, R. T. McNider, M. D. Moran, D. A. Moon, R. A. Stocker, R. L. Walko, and M. Uliaz, 1990. Regional and mesoscale modeling as applied to air quality models. *Proc. 18th NATO/CCMS International Tech. Meeting on Air Pollution Dispersion Modeling and its Application*, Vancouver, Brit. Columbia, pp.30

Quinn, F. H., 1978. Hydrologic response model of the North American Great Lakes. *Journal of Hydrology*, **37**:295-307.

Quinn, F. H., 1988. Likely effects of climate changes on water levels in the Great Lakes. In: *Proceedings, First North American Conference on Preparing for Climate Change*, Climate Change Institute, Washington, D. C., 481-487.

Quinn, F. H., and T. E. Croley II, 1983. Climatic water balance models for Great Lakes forecasting and simulation. In: *Preprint Volume: Fifth Conference on Hydrometeorology*, American Meteorological Society, Boston, Massachusetts, 218-223.

U. S. Environmental Protection Agency, 1984. *Potential Climatic Impacts of Increasing Atmospheric CO_2 with Emphasis on Water Availability and Hydrology in the United States*, EPA Office of Policy, Planning, and Evaluation, Washington, D. C.

U. S. Environmental Protection Agency, 1989. *The Potential Effects of Global Climate Change on the United States. Report to Congress.* J. B. Smith and D. A. Tirpak, Eds., Report EPA-230-05-89-050, EPA Office of Policy, Planning, and Evaluation, Washington, D.C.

5.2 PHYSICAL/CLIMATE SYSTEMS BREAKOUT GROUP PARTICIPANTS

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5.3 BREAKOUT GROUP REPORT

5 Year Research Plan and Products:

1. Develop 50-200 years BP (before present) climatology for all relevant fields.
   - identify spatial and temporal reporting/averaging intervals
   - identify target parameter fields
   - identify more specific focal sites?
   - should fields be spatially contiguous?
   - define priorities; including anthropogenic effects/impacts
   - agree upon a base climatology (more than one?) for group- wide analysis
   - complete first iteration in 2 years; update every 2 years

2. Develop "historical reconstruction" of climatology 1000- 4000 years BP.

3. Develop a derived-field data base and test scenarios; metadata.
   - incorporate into group-wide climatology

4. Define relationships between physical climatology and longer-term
   - variability in other (environmental and socio-economic) parameter fields.

5. Develop regional-scale atmospheric-surface-property dynamically coupled model components & evaluations.

6. Develop fine-scale (resolution), common-grid model for atmospheric-surface-property interaction.

7. Develop appropriate measurement/monitoring strategies for both model development (numerical and statistical) and testing.

8. Develop "high impact" forcing-response scenarios.
- IJC study results; review and recommend further work

"Catastrophic events accelerate political processes/responses."
- Should there be a specific effort to address the above?
- Flip-side: What parameter ranges induce "crisis" action- response?

9. Work to improve adaptability and range-of-applicability of existing model components (both numerical and statistical)
- remove "black box" relationships where possible.
- add process-specific subcomponents that are dynamically motivated.

10. Use more than one GCM to develop climate scenarios.

Other Products:

Suite of variables from various regional-scale models
Distributed and aggregated spatially and temporally
Result summaries for non-physical scientists
Community models
Generalized indices customized for impact studies
Result summaries for non-physical scientists

Critical Issues:

Demand by impact studies
Will there be climate change?
Do we know its large-scale characteristics?
Dissemination of information with users understanding limitations
Physical systems:
-Lake circulation
-Lake thermal structure
-Ice cover
-Water supply, lake levels, flows
-Lake water management
Quantification of uncertainty and variability
Water quality

Research Objectives:

Regional-scale models of coupled physical system:
-Atmospheric thermodynamics and circulation
-Lake thermodynamics and circulation
-Ice cover
-Land surface hydrology and water supply
-Improve methodology for all of above
-Large-scale studies now, finer scale later
Evaluation of previous work (GCMs and process models driven by GCMs)--are they good enough?
Define the present climate, including variability
Monitoring of climate, water, and hydrologic variables
Develop datasets of surface properties for models
Develop community models for distribution to scientific users
Feedback from other man-made factors (trends in consumption,
diversion, irrigation, etc.)
Development of appropriate products for impact studies
Can large lake conditions be used as a proxy of climate change?

RESEARCH ISSUES

Make presently-available data more applicable to localized impact studies.
Identify socio-economic impacts and their data needs.
Quantify uncertainty to accompany data.
Improved visualization.

6.0 WATER POLICY AND MANAGEMENT

6.1 ISSUE PAPERS

Water Policy and Management

by
Peter P. Rogers and Nagaraja Rao Harshadeep
Harvard University

ABSTRACT

Recently, the effects of the predicted global climate change have been receiving a lot of attention. The climate predictions are made by General Circulation Models (GCMs) and, although they tend to agree on their global average estimates of climatic variables, their regional predictions vary tremendously. One of the most important effects of these predictions in strategic areas such as the Great Lakes basin is the set of hydrologic effects which translate into socioeconomic impacts so that adaptive measures may be taken. However the estimation of the hydrologic impacts of climate change is beset with many problems.

This paper tries to outline the issues involved in the estimation of the hydrological impacts of climate change. It reviews the research being conducted in these areas, examines some of the techniques being used, reports on some of the research conducted on these areas by the authors and indicates the areas with a need for immediate research for the Great Lakes basin before a sensible water policy can be formulated for the region.

The issues of uncertainity in water resources planning and the consideration of the additional uncertainty of changed climate is outlined in this paper. It examines the tough situation faced by water resource decision makers who may not be able to change the way they operate even if the climate changes were almost exactly predicted. This paper also looks at statistical comparisons of climate change predicted by different models and illustrates the use of groundtruth as a baseline for the comparisons. Various model options that could be used by water resource planners are outlined. The results of GLERL model runs for different GCM predictions to estimate hydrologic variables in the Great Lakes basin are discussed. An outline of the research issues to be considered before the hydrologic and hence socio-economic impacts can be determined under a changed climate is presented for discussion.

INTRODUCTION

Climatic conditions influence all aspects of life on earth and shape the physical, biological, and socio-economic environment, all of which in turn influence the state and composition of the atmosphere (and ultimately climate). In other words, strong interactions and feedback loops exist between the various components of the ecosystem. Human activities are influenced greatly by weather and climatic conditions, and man can intentionally or inadvertently modify weather, climate, the water cycle, and such geochemical cycles as the carbon cycle (an alteration that leads to buildup of carbon dioxide in the atmosphere and subsequent warming).

Global warming (or rather climate change - given that although models predict warming on a mean global scale, regional forecasts may call for warmer or colder weather) is expected to have a substantial impact on the hydrologic cycle. In dealing with the effects of climate change on water resources, there are essentially three things to be determined: the future **availability** of water, the future **demand** for water, and the **consequences** of both of these on the environment. The problem is that each of these can be determined only to some level of certainty.

Unfortunately, water-resource decisions for the future have to be made today irrespective of the uncertainty associated with the above phenomenon. What is to be done? To design any adaptive hydrologic strategy for climate change, it is necessary to determine the hydrologic impacts of climate change. Given the large lead times in initiating water resource projects, one cannot adopt a totally "wait-and-see" attitude. The next best option is to model the climate-water system (a number of methods are described in this paper) while keeping in mind the assumptions in the modeling process to predict future hydrology, and consequently its socio-economic effects under conditions of climate change. Then, water resource decision makers can evaluate these findings and determine if any unusual actions are needed given the nature of the predictions and the uncertainties involved. Stakhiv (1993) feels that current techniques and tools for water management and analysis are adequate to cope with water resources management under climate change, without the need for undertaking extraordinary measures.

The major manifestations of socio-economic consequences of climate change on water resources, both quantity and quality, will be felt though shifts in the availability of the resource and in shifts in demand for the resource. In addition to these direct effects there are also secondary impacts of socio-economic change which will impact the aquatic system which, in turn, will impact upon climate, and which in turn will influence water availability. Climate will also directly influence economic uses of land and water use which will influence water availability and so forth. These potential interactions are shown schematically in Figure 1. In this figure, first order effects are the directly obvious effects of one change on another. For example, an increase in precipitation causes a river to flood, this in turn floods part of a city. These are both first order effects. If, however, as a consequence of this flood the city builds extensive dikes and levees, then the water will be kept off the land and groundwater recharge will be depleted. This is a second order effect. From the point of view of water resources, the emissions of greenhouse gases from urban areas in response to increased demand for air conditioning because of climate change are considered second order effects.

How far one should pursue this cycle depends upon the magnitude of the impacts and also upon the time-scale of concern. For most practical decisions, consideration of only the direct (first order) effects is sufficient. For intermediate term decisions, consideration of the primary and secondary effects may suffice. For long-term considerations, of the same order as the predicted greenhouse gas doubling, examination of all three pathways may be necessary.

FIGURE 1
Socio-Economic Consequences of Climate Change

As far as the socio-economic system is concerned, climate change will be manifested through changes in temperature, precipitation, sea and lake level rise, and storm frequency. For each of these effects how the mean behavior will change is important, but the change in variability, seasonality, and extremeness of the effects will be equally important. The frequency and intensity of storms and surges have great potential for exacerbating or ameliorating damages depending upon which direction the effects will go. There are other important effects which are derived as a consequence of changes in temperature and precipitation that are extremely important from a socio-economic point of view. For example, the parameters soil moisture and evapotranspiration, which depend directly upon precipitation, temperature, and also upon soil and vegetation type, determine how successful agriculture will be with, or without, irrigation. Since in many regions, irrigation consumes upward of 80% of all water used, the impacts of climate change upon soil moisture and evapotranspiration will be the most critical impacts in assessing socio-economic consequences of climate change.

The benefit of over 40 years of economic research on water resources is that it is a fairly easy task to assess the first order socio-economic effects of climate change, provided, that we have reliable forecasts of the means, the variances, and the skew coefficients for the various hydrological inputs. It is impossible to list all the studies on national, regional, river basin, and local levels over this time period. Several journals and many books give the details of the assessment methodology. The weak point in the assessment methodology tends to be in dealing adequately with uncertainty in estimates of the input data to provide reliable forecasts into the future. Incidentally, much of the uncertainty arises from estimating the economic parameters -- **not** the hydrological ones. Despite the global averages, it is the temporal and spatial distributions of precipitation that are the major determinants of the habitability of land for human uses. For example, where rainfall is seasonal, water availability is limited at certain times of the year and, in some cases, where precipitation also varies greatly from year to year (particularly in the semiarid tropics); this can pose problems for agriculture and other settled human activities. Spatial variability in precipitation also has great significance in ecosystem stability. The precise nature of the impact depends on many factors and defies generalization, but in semiarid areas, variability can be devastating.

GREAT LAKES REGION

The Great Lakes contain about 23,000 km^3 of water, which represents about 18% of the world's (and 95% of the U.S.') fresh surface water (USEPA and Environment Canada, 1988). The lakes are intensively used for navigation, hydropower, irrigation, water supply, recreation, and as habitat for fish and wildlife. Studies of the regional hydrologic cycle in the Great Lakes Basin have revealed that much of the moisture in the region is a result of evaporation from the surface of the lakes that occupy about one-third of the total basin area. The lake levels are a function of the net basin supply to the lake, which in turn depends on the surface runoff into the lake, the precipitation onto the lake, and the evaporation from the surface of the lake along with diversions and consumptive uses. Net groundwater flows into the lakes are negligible (Croley, 1989).

The Great Lakes basin is an important region for the United States. The population in the region has been estimated to be more than 29 million in the U.S. and 8 million in Canada. Major industries include hydroelectricity, agriculture, and wood products. It is also an important shipping corridor. The immense recreation benefits derived from the lakes might be adversely affected by changes in lake levels. Past changes in lake levels have resulted in flooding and severe flood damages to newly developed shoreline properties.

CLIMATE CHANGE

In the last decade, global climate change and its potential impacts have received a lot of attention. In the case of water resources, this has centered on climatic impacts caused by potential global warming, attributed mostly to a build-up of greenhouse gases (primarily CO2) in the atmosphere, leading to an increase in the heat-trapping capability of the atmosphere, resulting in higher global average temperatures. Complex GCM's have been constructed on a global scale to predict climatic variables under scenarios of increased greenhouse gases. These include models by the Geophysical Fluid Dynamics Laboratory (GFDL), the Goddard Institute for Space Sciences (GISS), Oregon State University (OSU), National Center for Atmospheric Research (NCAR), the United Kingdom Meteorological Office (UKMO), and the Canadian Climate Center (CCC). These models all predict an average global temperature increase of a few degrees centigrade. The use of these models for hydrological purposes is beset with a number of problems including:

- Low Spatial Resolution of Grids
All the GCMs have very coarse grids to make the models manageable for computation. For example:

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- Low Spatial Resolution of Grids

All the GCMs have very coarse grids to make the models manageable for computation. For example:

MODEL	NAME	RESOLUTION
GISS	Goddard Institute for Space Sciences	7.83°lat. x 10.0°lon.
GFDL	Geophysical Fluid Dynamics Laboratory	4.44°lat. x 7.5°lon.
OSU	Oregon State University	4.00°lat. x 5.0°lon.
UKMO	United Kingdom Meteorological Office	2.5°lat. x 3.75°lon.
CCC	Canadian Climate Center	3.75°lat. x 3.75°lon.

To give an example of exactly how large an area each one of these grid cells covers - six cells of the GISS model cover not only the entire Great Lakes region (lakes and basins) but also the states of Wisconsin, Illinois, Indiana, Ohio, and Michigan. Although hydrologists desire much more detailed predictions, there is little chance of this happening soon; (for example, it is estimated that to have a resolution of a small watershed (30 km x 30 km), it would require two days of supercomputing time to predict one day of climate!). In order to forecast hydrologic impacts of climate change, one has to use the best available data for climate change.

- Model Confidence

It has been pointed out (Merns, Gleick, and Schneider, 1990) that coupling of ocean-atmosphere GCMs still has to be studied in detail along with the estimation of transient climates (e.g. between $1xCO_2$ and $2xCO_2$). In addition there is a major problem of temporal scale (e.g. some models do not have a diurnal insolation cycle, although GCM output can be produced for every 10 minutes!). It has been argued that there is excessive parameterization of important variables such as cloud cover. However, as GCM complexity increases, their computation requirements increase tremendously. The simplistic equations used to describe hydrological processes also tend to oversimplify predictions (e.g. introducing seasonality in precipitation where none exists).

GCMs are all based on a few equations that attempt to capture the complexity of the atmospheric circulation and interaction with the global terrestrial, hydrologic, biospheric, and energy cycles. An assumption is inherent in this approach: that the interactions mentioned are quantifiable and that the representative equations generated can approximately predict climate. This assumption has been challenged with the advent of the field of Chaos Theory (Gleick, 1988) which suggests that highly non-linear systems such as the climatic system tend to be chaotic and not predictable.

- Disagreements among the GCMs

These models all seem to agree that the earth's temperature would go up by around 3°C to 4°C. But the forecasts for precipitation range from an increase of about 4% to 15%. Even the apparent agreement of temperature predictions is valid only at a global scale - it breaks down if one were to view the predictions at a regional scale. In fact, the differences among the model predictions of temperature, precipitation, wind speed, etc. differ widely in many regions of the globe. For example, Moreau (1988) compared the GISS and GFDL models and discovered not only differences in *magnitude* of changes of precipitation and temperature, but also differences in the *direction* of the effects. GISS shows a 5 to 15% increase in precipitation and, for the same region, GFDL shows a 5 to 15% reduction in precipitation. Hence, the differences could be as large as 30% if precipitation has to be predicted. Other commentators on these differences include Schlesinger and Mitchell , for GFDL, GISS, and NCAR. Grotch (1988), and Schneider, Gleick, and Mearns (1990) also highlight these differences. If predictions by different GCMs do agree for certain variables and regions, that may not be taken as a sign of extra reliabiity in those predictions as the agreement may be either because the models are based on the same assumptions or because of chance.

- Disagreement between GCM and goundtruth(s)

There are not only problems in reconciling the climates under doubled greenhouse gas predicted by the models with each other, but there is a much more fundamental prediction problem which only became obvious from Jenne's paper (1989); the fact that each of these models bases itself on some "groundtruth" like the RAND climate and then uses this as a starting point to estimate its own starting climate (or $1xCO_2$ case). The situation is further complicated by the fact that the GCM models do not compare themselves to some objective groundtruth, but rather, compare themselves to their own version of the predicted $1xCO_2$ climate. This leads to some ambiguity about actually how to compare the output from the GCM's with each other. Should one compare the absolute numbers to each other? Should one compare the ratios of $2xCO_2/1xCO_2$ and then compare these to the RAND $1xCO_2$ data to arrive at numerical estimates? Should the models be evaluated on the basis of their ability to predict the present climate? Some interesting philosophical points arise as to the advisability of relying upon predictions based upon models which start out with a poor representation of groundtruth.

Even knowing the groundtruth itself is a complex problem. For example, both the RAND Corporation and NASA have their own (and different) estimates of the current climate. Figure 2 shows the differences between the RAND and the NASA climates. Over the U.S., RAND underestimated the annual NASA precipitation by 0.21 mm/day. However, the standard deviation on this estimate based upon the individual observations was almost twice as big as the estimate itself, indicating that there are only marginal differences between the two climates. In this paper we have followed Jenne (1989) and used the RAND climate as the basis for our comparisons of GCM outputs.

In a study at Harvard, we performed a number of spatial statistical calculations on the GCM outputs of temperature and precipitation against groundtruth and GCM $1xCO_2$ estimations on the $2xCO_2$ predictions. We found that there was a great discrepancy in the $1xCO_2$ estimates for the GCMs and the groundtruth, indicating that the GCMs were being run for the next few decades with a questionable starting point. In addition, we found that, for most GCMs, there was an excellent fit of $2xCO_2$ predictions in the grid cells covering the U.S. with $1xCO_2$ estimates - so much so, in fact, that in many cases, a simple linear regression (or scaling) may have sufficed to predict that variable in each grid cell instead of simulating decades on the GCM! However, much more research is needed in using extended ($4xCO_2$, etc.) and transient forecasts to examine this property of predictibility of the predictions.

- Extreme value prediction

The design of water resource systems is always driven by extremes (floods, droughts, etc.). GCMs give us predictions for mean or average values of climatic variables. Mapping these average values into extremes to examine the all-important tails of the distributions warrants further research.

- Differing Time-Scales

Perhaps the most important factor in the inclusion of climate change in water resource decision-making is that climate forecasts are usually reported for scenarios that are at least 50-100 years away - This is the scale at which climate-modelers work, whereas water resource managers have to make decisions today for the short-term, and have to work with a political decision-making system that plans for a still more short term. In addition, the decisions are based on a large uncertainty anyway, as explained in a later section.

HYDROLOGICAL EFFECTS OF CLIMATE CHANGE

The climate of a region is extremely dependent on its hydrology and vice-versa (this is particularly true of the Great Lakes region). GCMs are extremely sensitive to factors such as changes in cloud cover and temporal and spatial distribution of snowpack as hydrologic models are to changes in climatic variables such as temperature and precipitation. In the interests of computation efficiency, however, hydrologic processes are lumped in GCMs and simple parameterizations or simplified assumptions are made to estimate climatic variables, which are then used to generate the hydrologic parameters in detail. All this makes the estimation of the effects of climate change difficult.

Many techniques have been proposed and used to model the hydrological effects of climate change. These include:

- Coupling GCM outputs with Hydrologic Models

This approach usually involves estimating the effects of climate change on different parameters of hydrologic models and then running these models either with **modified data** or **modified hydrologic equations** or both. For example, the GLERL hydrologic model is a fixed accounting model that runs future climate scenarios with input historical climate data scaled up by the GCM mean forecasts. Another approach is to assume that streamflow change is directly related to runoff changes (which is either assumed to be proportional to precipitation changes or estimated otherwise). Other researchers have examined the effect of climate change on the estimation of specific hydrologic parameters that describe different components of the hydrologic cycle. For example, Rosenberg, et al. (1990) report on the effects of climate change on evapotranspiration.

The traditional approach to this is to assume that the GCM output is correct, assume that the historical data sets are correct, assume that the hydrologic and other models are correct, and then model the effects of climate change. This usually ignores uncertainties in the values of climatic variables; also, this assumes that the hydrology is dependent in a predictable way on important climatic variables such as temperature and precipitation. The problems of grid scale and accuracy are extremely important here. This leads to problems such as:

- incompatible grids for models and GCMs - scaling and interpolation errors.
- scaling-up of historical input data may not be representative of future scenarios.
- there is usually no forecast GCM output to change many input parameters which are subsequently to be invarient to climate change.
- models are usually too deterministic and extreme events are not handled well.

The hydrologic models used may be of many types, depending on the purpose of use:

- Computer Simulation Models (such as GLERL and other hydrologic accounting or water balance models).
- Optimization Models (for optimal reservoir releases, storages, allocations, etc.).
- Simple Analytical Models (includes regression-based lumped river basin models (e.g. linear and non-linear models described in Schaake (1990)) and stochastic basin models such as the abc, abcd, abcde family of models (the abcd model is described in Rogers and Fiering (1990))).

\- Regional GCMs and Coupling with Hydrologic Models

Mearns and Rhodes (1993) report on attempts to build regional GCMs to more adequately account for the large effect that the Great Lakes have on the climate of the region. One approach described is to nest a high resolution regional climate model (REGCM) in a global climate model (GCM) by using GCM predictions as boundary conditions for the REGCM. Efforts are also underway to couple a lake model to the REGCM in a fully interactive mode to provide hydrologic information for use in more detailed hydrologic and other models. It appears that this sequence of nested models is the most efficient method to generate specific information on a more useful scale, although there is a danger of compounding model and data errors through the system.

\- Extended Streamflow Prediction

The National Weather Service uses a technique called Extended Streamflow Prediction which is a long-range probabilistic forecast of stream flow, involving the generation of conditional probability distributions assuming each historical year is equally representative of the current climate. However, there are problems in modifying ESP generation with climate forecasts (Schaake, 1990).

\- Modified Synthetic Streamflow Generation

Fiering (1967) suggested the use of synthetically generated sequences of streamflows for modeling the future instead of relying on historical data alone. The effect of climate change can be incorporated by estimating streamflow under modified parameters (usually mean, standard deviation, auto, and cross correlation coefficients and skew of the historical flows) of the streamflow generating model. Such an approach has been used by Schwarz (1977) with arbitrary changes in a sensitivity analysis on four parameters with little noticeable change in water supply distributions. The advantage of such models is the limited data requirements, but the output lacks the detail of more complex models. These models tend to best illustrate that the hydrologic processes are so stochastic that the use of even near-perfect knowledge of future climate changes may be dwarfed by natural variability.

Matalas and Fiering (1977) have suggested the use of the probabilistic concepts of the 3Rs (Robustness, Regret, and Resilience) in a comprehensive approach to water resources planning in the uncertain environment of climate change.

In addition to the **supply**-side hydrological changes resulting from climate changes as addressed above, the **demand** for water is also expected to vary under changed climate. However, these are extremely difficult to forecast and are usually handled by simplified regression analysis to determine water needs for different uses as a function of climatic variables.

UNCERTAINTY IN WATER RESOURCES PLANNING

As discussed above, the role of uncertainty in making socio-economic assessments of the effects of climate is the fundamental problem facing policymakers. It has long been recognized by water-resource planners that extreme events dictate detailed planning, design, and operation of their systems. Dams and levees are constructed and operated in response to floods and droughts. For example, following the great northeast floods of 1955, when Hurricanes Connie and Diane ravaged the region twice within a week, a number of reservoirs were constructed to help control flood flows in the Connecticut, Delaware, and other basins. Now, almost 40 years after the fact, and following a period with relatively few hurricanes, these structures stand largely unused, with little history of having protected anything against a major flood. Even though they were designed using standard procedures, they are a potential embarrassment unless they can be put to some other use or provide flood protection under changed climate conditions.

By their very nature and rarity, extremes (at both ends of the scale, floods and droughts alike) do not define a large enough sample to allow deterministic or statistical basis for design. Historically, planners have used critical periods of record, empirical corrections to observations, statistical procedures based on prescribed density functions, even synthetic events to help generate realistic design values. While many of these techniques are useful in the orderly world of mean flows, where the Central Limit Theorem governs, they have failed to capture the true (and dangerously large) departures that are characteristic of natural phenomena and that designs are based on. Indeed, in recent years a whole discipline, Chaos Theory, based on unstable fluctuations of typical records has been invented. To counter this irregularity, Fiering and Rogers (1991) tried a variety of statistical formulations; however, the density functions they used were typically too smooth and too well behaved to reproduce historical extremes reliably enough to serve as useful adjuncts to the planning process. For example, in the case of Hurricanes Connie and Diane, the statistical characteristics of either storm alone could be generated by a number of statistical tricks. However, their combined effect could not be produced without artificially and rather arbitrarily juxtaposing the two storm events; this is because apart from the one historical event formed by the two storms, nothing in the record even remotely suggested the possibility that such a catastrophe might occur.

Looking at actual hydrology can be quite misleading. For example, Parry and Carter (1986) show what might happen when the mean of a probability distribution of streamflows is decreased and the variability increased. Information of this type **ought** to be very useful to the water planner, however, consider how the information that the mean streamflow would decrease by 20% and that the standard deviation would increase by 10% over a period of 60 years would be viewed by a typical water manager.3 He, or she, would estimate the likely flows over the next 60 years using some sort of stochastic simulation model and obtain results that are virtually indistinguishable from the original data (see Figure 3). Even though we know **exactly** the change in climate, at least for about the first 40 years of the simulated time series, the decisions the manager would make would be no different than if he, or she, had not been presented with the new information.

In order to predict the socio-economic consequences of climate change we need to estimate the parameters of the future climate in terms of temperature, precipitation, etc. We also require estimates of their inherent variability. Unfortunately, this forces us to rely upon guesses or the output of the GCMs, and the sources of uncertainty when using GCM output are difficult to specify. Two recent reviews (Gleick, 1990; Rind *et al.*, 1992) highlight the problem of GCM output being too coarse-scale for modeling hydrologic processes. In addition, soil moisture algorithms used in GCMs have been overly simplistic (Gleick, 1990). The same holds true for evapotranspiration (Rosenberg *et al.*, 1990). An improved representation of terrestrial hydrological processes, for instance, in the GCM developed at the Geophysical Fluid Dynamics Laboratory (GFDL) has demonstrated that GCMs previously greatly overestimated the value of potential evaporation, so that modeled soil moisture was seriously underestimated in seasons of water shortage (CEES, 1992, p. 19).

The GCMs provide average precipitation and temperature values on temporal and spatial scales that are too large to make reliable designs of, and operating policies for, water resource systems such as reservoir systems. Apart from unavoidable and irreducible uncertainties in GCM output, there is a real need to translate that output onto a finer grid and to interpolate extreme values where the GCMs provide temporal and spatial averages. Climate stresses are generated at large scale and must be mapped into event sequences at basin scale so that regional and local hydrological phenomena, and particularly hydrologic extremes, can be anticipated in a statistical setting; these smaller scale phenomena are the bases of regional planning and engineering design.

And those rare events that dictate hydrological design are drawn from

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This is at the extreme levels of predicted outcomes from climate change in the U.S. For example, for the Colorado Nash and Glieck (1990) reduced the earlier predictions of declines in annual flow from over 40% to 14 to 23% for a 2-degree C temperature rise coupled with a 10% decrease in precipitation.

distributions, which are perhaps non-stationary and poorly defined at best. Their parent densities might be quite distinct from those which govern ordinary events. How should these be described? How do they enter the design process? And will they change as a function of global climate change?

Rind *et al.* (1992) set forth a number of unresolved hydrological research questions which reflect hydrological uncertainty in a review of hydrologic modeling in the context of climate change. These include:

1. Can runoff and infiltration be calculated accurately enough from basin models that have relatively coarse vertical and horizontal resolution?
2. Does small-scale heterogeneity overwhelm averaged values of surface parameters?
3. How do we model sub-grid-scale soil moisture?
4. What are alternative formulations for potential evapotranspiration (PET)?
5. Can large horizontal gradients in soil moisture exist between a forested and agricultural landscape for long periods of time?
6. Is drainage through a permeable bottom layer necessary for accurate representation of surface hydrology?

THE GLERL MODEL

The Great Lakes Environmental Research Laboratory has developed a daily model for simulating the hydrologic budget of 121 subwatersheds draining into the Great Lakes. This includes the estimation of moisture storages, runoff, over-lake precipitation, heat storages, and evaporation from each of the lakes using climatic data as input.

In a study conducted at Harvard University, we have examined the predictions of four popular GCMs (GFDL, GISS, OS and UKMO) on the Great Lakes basin. We have also analyzed these predictions using pattern recognition techniques to determine how they correlate with groundtruth. We have obtained very high correlations for a simple linear model to predict 2xCO2 from 1xCO2 simulations for some GCMs, which may indicate a misplaced emphasis on running these models over many years for this region. We then use these GCM predictions to modify the GLERL model for the Great Lakes Basin to estimate the hydrologic impacts of these predictions. We find that, except for a few instances, the models predict widely varying values for hydrologic parameters. This is not surprising considering the high variance in the climatic predictions of the GCMs. This is an essential step before socio-economic effects can be evaluated (this was not possible at this stage because of the lack of a model to predict lake levels compatible with the GLERL model output).

The GLERL program was developed with a view to simulating the hydrology of the Great lakes region; it is not intended as a forecasting model to predict the effects of global climate change. However, we have made an attempt to modify the input data for GLERL according to GCM forecasts in order to compare the socio-economic impacts of hydrologic predictions based upon the GCMs.

The GLERL package uses many hundreds of files for input and output and is not very easy to modify. It uses climatic variables to forecast daily values of different hydrologic variables such as runoff, snowpack, groundwater storage, etc. One important variable that directly relates to lake levels is the Net Basin Supply. The Net Basin Supply (NBS) to each of the lakes is estimated by the following relationship:

$$NBS = P_i + \sum_{j=1}^{n_i} R_{ij} - E_i$$

where:

NBS_i is the net basin supply to lake i,
R_{ij} is the surface runoff from subwatershed j of lake i,
P_i is the precipitation over the lake i,
E_i is the evaporation from the lake surface,
n_i is the total number of subwatersheds contributing to lake i.
i represents the Lakes Erie (n_i=21), Huron (n_i=29), Michigan (n_i=27), Ontario (n_i=15), Superior (n_i=22), and St. Clair (n_i=7), and

Further description of the model components can be found in Croley (1990). The GLERL Large Basin Runoff Model (LBRM) uses daily precipitation, temperature and insolation to determine the surface water runoff by estimating the other components of the hydrologic cycle. This model was calibrated generally over 1965-82 to minimize the sum-of-the-squares-of-the-error-terms between calculated and observed runoff flows. Over lake precipitation, P_i, was estimated by using overland measurements. This may result in problems as this tends to ignore lake effects which may be significant, especially over such large lake surface areas. The lake evaporation term E_i was estimated by a coupled heat-storage and evaporation model that uses daily air temperature, dewpoint temperature, wind speed, and cloud cover to also determine lake heat fluxes and storage, and surface temperature.

Some Problems with the GLERL Model:

- The model is too "black-box"-ish.
- Too tied-in with present conditions and historical data.
- Only a few variables can be easily changed.
- Changing the data where it is allowable is not simple. There are a multitude of files that are in direct-access format (not ASCII to reduce storage requirements) which need special editors. This makes changing input data rather slow and painstaking.
- In general, too much effort is devoted to data management.
- The user-interface for input and output needs to be improved greatly.
- There is no consideration of changes in landuse in the model.
- Calibration with present climate has been done only for the runoff model component of GLERL.
- It is a simple accounting model and stochasticity has not been dealt with at

GLERL.

- Currently, it has not been adequately interfaced with lake-level models.
- There is little documentation for the GLERL model and details of previous applications.

SOCIOECONOMIC IMPACTS OF CLIMATE CHANGE IN THE GREAT LAKES BASIN

There have been some studies on the potential economic consequences of climate change on water for the Great Lakes region in the U.S. and Canada. The data on potential economic impacts due to climate change is presented the First North American Conference on Preparing for Climate Change (1987) and the First United States-Canada Symposium on the Impact of Climate Change on the Great Lakes Basin (1988). These data indicate the magnitudes of the impacts, and could form the basis for more detailed explorations. Most of these studies used some version of the GISS model with doubling of atmospheric carbon dioxide as the basis for predicted outcomes. The doubling is expected to occur by the year 2050. Croley (1988) has summarized some of the impacts in a schematic framework as shown in Figure 4.

For the Canadian portion of the basin Cohen (1986) predicted:

- a 15% reduction in net basin water supplies,
- lake levels at their 1963-65 levels (the lowest this century),
- an annual loss of 2400-4200 GWh of hydro-energy on the Lake Ontario outflows (CAN$34 to CAN$65 million based upon 1979 data),
- a reduction in electricity demand due to climate warming equal to 6400-7600 GWh resulting in annual savings of CAN$99 to CAN$118 million,
- annual navigation economic loss of U.S.$27.8 million due to reduced lake levels,
- economic losses of CAN$36.5 in recreation due to loss of snow cover in the area's ski resorts,
- an increase in the economic benefits of camping recreation of CAN$14 million due to extension of the summer season,
- a 7% decline in Ontario's agricultural output due to moisture stress (leading to economic losses of from CAN$101 to CAN$170 million per year), and
- a 2.6% increase in demand for municipal water supplies for lawn watering, etc.

The implications for waterborne transportation as reported by Hartmann (1990) are as follows:

- Change in depths (i.e. lower levels result in more trips to move the same tonnage). Therefore, we would have higher shipping costs and more bottlenecks.
- Decreased ice would result in more time that would be available to navigation.
- Decreased flows and water levels would reduce power production potential. Hartmann gives examples of what happened during very low levels in the 1960s.
- Peak power demand is in the summer months and would be substantially affected by

climate change. Add to this possible changes of lake levels and one could see severe consequences.

The effects on other sectors (Hartmann, 1989 - GLERL paper 645), are as follows:

- Many businesses whose operations are closely linked to the shoreline would face some short-term difficulties but could eventually move to higher or lower locations. But lower lake levels would require dredging when it came to small craft operations and private/municipal harbors. These changes might be prohibitively expensive for many private individuals or small municipalities.
- Recreation that depends on certain lake levels and lake cover might be hurt. For example, ice fishing might not be possible if there is a very thin ice cover for a very short time.
- Commercial fishermen might face tremendous problems as changes in lake levels and turnovers might affect the types of fishes available for harvesting. Damages to wetlands could have deleterious effects on the food chain thus leading to further changes in fish populations.
- Agriculture depends on soil fertility which could be affected by lake levels. There will probably be a trade-off between changes in the winter and summer months. Changes in soil moisture could change the crops or make new demands on irrigation.
- Recreation plays a huge role in the overall economic picture of the Great Lakes region. Loss of wetlands from lake level change could have adverse short-term effects, but it is not difficult to foresee all recreation activities just moving with the shoreline. Yet, as previously mentioned, the long-term loss of private and public marinas could permanently damage recreational boating.

Good data do not exist for navigation benefits, but Raoul and Goodwin (1987) cite an additional U.S.$50 to U.S.$60 million per year as the value of increasing Lake Superior's navigating depth from 27 ft. to 28 ft. Marchand *et al.* (1988) studied the effect of climate on the economy of Great Lakes shipping. They applied GCM output for doubled carbon dioxide, a regional hydrological model, and a regional Great Lakes economic model, and found that mean annual shipping costs could rise by as much as 30% under plausible scenarios. The analysis allowed testing the benefit/cost ratio of policy options for maintaining artificially higher water levels.

No data were available for the environmental implications for water quality (see paper by Blumberg and DiToro (1988) which predicts losses of 1 to 2 mg/l of dissolved oxygen in Lake Erie due to temperature effects alone), wetlands and fisheries (a 20 cm lowering of Lake Huron-Michigan levels could affect 64% of all the U.S. Great Lakes wetlands), water supply and waste disposal for industry, commercial operations, recreation, and commercial fishing.

HYDROLOGIC IMPACTS OF CLIMATE CHANGE ON THE GREAT LAKES BASIN

Croley has used the GLERL model to predict hydrologic effects and has reported extensively on this subject. In Mearns and Rhodes (1993), he describes the results of research using the GLERL model to compute the net basin supplies to the Great Lakes using $1xCO_2$ and $2xCO_2$ simulations provided by the Environmental Protection Agency (EPA) and the Canadian Climate Center (CCC). They report higher evapotranspiration, lower runoff, earlier peak runoff, reduced soil moisture, higher water temperatures, a greatly reduced snowpack and lake ice formation, and a drop in net basin supplies implying a general drop in lake levels. This corroborates earlier studies described in the report of the Phase I of the International Joint Commission (IJC) which used three different GCM outputs to estimate the effect of climate change on Great Lakes levels.

In a study conducted at Harvard (Fiering, et al, 1993), GLERL input climate data were modified by GCM predictions to simulate hydrologic effects. One of the aims of this study was to compare the effects of the predictions by different GCMs. One problem with this is that the GCM predictions vary widely, leading to substantially different predictions of hydrologic variables. As is the case with temperature and precipitation predictions of different GCM models, the hydrologic predictions also vary not only in magnitude but also in the direction of change. Generally, the findings varied widely depending on the lake being considered, and the results reported below should only be considered a representative average finding, with no bias as to the relative confidence one has in each model.

Due to the extreme variability in the global climate models' predictions for precipitation and temperature, it is very difficult to pinpoint the exact hydrological future for the Great Lakes region. Summarizing the results for $2xCO_2/1xCO_2$ ratios, and making very general conclusions and averages, the GLERL model found that runoff will decrease by approximately 20% for all of the Great Lakes except Lake Superior, where it will remain relatively constant. Net basin supply is predicted to fall slightly, with the exception of apparent near-constancy for Lake Huron, and a predicted 20% increase for Lake Superior. We may therefore make the preliminary conclusion that, under situations of doubled greenhouse gas levels, lake levels *may* increase for Lake Superior and decrease slightly in all other Great Lakes.

The story remains the same for total moisture storage in the ground, which is predicted to fall substantially (anywhere from 20-70%) for all except Lake Superior, which showed minimal change. The models were extremely variable for groundwater, but with the exception of deviant GFDL predictions, groundwater levels were predicted to drop in the 20% range for all lakes except Superior, where there was no detectable change on average. Evapotranspiration (ET) was another variable which was very difficult to predict, as the model results varied substantially. In general, the amount of ET was found to increase for all lakes, with the smallest gain for Lake Superior. For soil moisture, all models hovered around a 25% decline everywhere but Lake Superior, where a slight increase is seen on the average. Finally, snowfall was found to decline substantially for all lakes, but less so for Lake Superior.

Thus, taking the models as somewhat representative of what might actually happen, we found that Lake Superior is certainly affected differently than the other

Great Lakes by climate change. This can be partially attributed to the fact that Lake Superior is slightly geographically removed from the other Great Lakes, has a larger area and is colder. The climate effects of increased carbon dioxide varied tremendously by location, making global generalizations very difficult to attain. This affects the certainty of these conclusions, as the values of the data used were extremely dependent on the interpolation routine.

The final question arises as to how the GLERL results should be properly interpreted. The only historically verifiable prediction of these four models is their prediction for temperature and precipitation, which were found to be lacking in correlation with the actual RAND data, which itself may not represent the actual groundtruth. Thus, GLERL has been implemented with the predictions of models which are known to be error prone, while the robustness of GLERL itself is uncertain. It may be too premature to act at this point in time with our current understanding of the GCMs and the hydrologic processes on regional decisions that are based on predicted global climate change, especially as the GCMs considered in this study vary so widely in their predictions.

CONCLUSIONS

Spatial statistical assessments should help in evaluating the choice of GCM model for use in water resource policy studies. They may also be useful in helping the modelers assess which parameters in their models may be causing problems with goodness of fit with historical data. Another approach we took was to regress the $2xCO_2$ model temperature results against the $1xCO_2$ results for GFDL and GISS. The fit is quite remarkable, leading one to question the value of the $2xCO_2$ estimates of these models for this region if one can predict the $2xCO_2$ temperatures from the $1xCO_2$ results with just a simple linear regression model. Figure 5 shows the spatial distribution of the results and the estimates based upon the regression model. What is remarkable about these results is that the regression equations are very similar both in intercept and slope. Does this imply that the GCMs themselves are not necessary for predicting the future in this region? The different absolute values of the variables obtained by the models appear to be artifacts only of the initial calibration. Figure 6 shows a regression model for the precipitation from GISS. This model is not as good a fit as the earlier one -- but still significant. What is also intriguing is that the slope is almost identical with that of the temperature models for GISS and GFDL. This finding is also supported by the fact that, for all of the models, the contours of temperature and precipitation for $1xCO_2$ and $2xCO_2$ are virtually identical, with only nearly uniform magnitude changes distinguishing one from the other. What do these findings imply?

The GCMs may be useful to predict temperature increases on a global scale; however, most adaptive decisions have to be made on an assessment of effects at a regional scale. The GCMs do not seem to concur on predictions of climatic variables in the region and hence on the hydrologic effects. However, we have reported the general trends predicted by each model and their agreements. But much more research is needed before one can say how much of this is due to the limited data and modeling techniques and how much is due to future climate scenarios.

There are many uncertainties to be faced by water managers and planners. These uncertainties become ever larger when future climate change is contemplated. It appears from the literature (James, Bower, and Matalas, 1969 and Schwarz, 1977) that the hydrological changes may be among some of the least important. Nevertheless, water is, and will remain a critically important resource for maintaining ecosystems and economies. This may be paradoxical, but water use by humans has a remarkably wide range of substitutable uses -- the uses by nature may be far less substitutable and, hence, potentially more important under climate change. Moreover, uncertainty concerning water availability may be one of the most easily reducible of the inherent uncertainties.

The Potomac River case shows that the hazards of making errors in forecasting the demand for water, even for periods as short as 25 years into the future, are largely due to errors in estimating the socio-economic variables, not the hydrological variables. Essentially, the Potomac case tells us to make flexible plans which take advantage of existing facilities.

Of the hydrologic parameters, it appears that the two most important that water managers need to get from climatologists are the potential magnitudes of future water availability and its variability. The Potomac case makes clear that, once the economic and political uncertainties were resolved, managing the variability of the water supply is the most important aspect of planning. Therefore, if the climate experts were able to give us accurate estimates of the changes in the means, variances, skewness, and persistence of either the precipitation or the streamflows, then we could improve the accuracy of our plans for meeting future demands.

Given typical discount rates and economies-of-scale of water projects, the optimal planning period is usually less than 20 years (Thomas, 1971). Schwarz's results for the Potomac indicate that, even with very strong assumptions about the variability of the parameters of climate change, the range of responses of the system are well within the range of uncertainty about the social and economic parameters, and within the range of fairly easy adaptation if required.

The recent Californian drought presented the best evidence of the adaptations available in modern U.S. circumstances. While the adaptations are by no means painless, the magnitudes of the seeming "shortfall" in California were far beyond what could be expected under climate change scenarios. For California, it would appear that we should not be worrying excessively about climate change given the demonstrated ability of the socio-economic system to adapt. The literature on actual cases involving large stresses on water systems, taken as a whole, indicate that even if we know the future hydrological parameters exactly, we probably would not change how we currently carry out water planning and management in the United States (Stakhiv, 1993). The existing systems appear to be flexible and adaptive enough to withstand large changes in water availability and increased demand. This does not mean, however, that we should not concern ourselves with climate change. We should. What it does mean is that we should not be stampeded into taking inappropriate actions. There is a growing clamor for preemptive action even before we know the consequences "because the costs of being wrong" may be catastrophic. Obviously we should keep our eyes open for the occasional catastrophe -- one good catastrophe can ruin your whole day! How do we avoid the catastrophes? We do this by continuing to carry on research on the nexus of climate change, water resources, and socio-economic adaptation; not solely on the hydrology but also on other parts of the socio-economic system and the aquatic ecosystem. The one area that stands out from the California case as a potential catastrophe is the consequence of possible climate change upon stream biota and other ecosystems dependent upon water. These are largely being neglected by a science policy which misallocates the climate research monies to large scale climate modeling at the expense of these potentially more valuable areas of knowledge.

We believe that this paper demonstrates that while there appears to be little need for a new methodology to assess the socio-economic consequences of climate change, there is the need for more research on the reliability of, and mechanisms for, predicting the hydrological consequences of climate change, and upon the adaptation of water resources systems to climate change.

RESEARCH NEEDED

- There is a need for simpler, more interactive models. Models should take advantage of new tools available on microcomputers and workstations to be user-friendly in operation, have a knowledge base, be flexible to work under different assumptions, equations and relationships, and have well-defined and presented inputs and outputs. There is no need for good models, however complex, to be "black-box"-ish today with all the recent advances in computer software and hardware. The GLERL model problems mentioned in this paper could also be addressed in future research. It may be worth substantially modifying the GLERL model to incorporate some of the suggestions here.
- In many models, too much effort is spent on data management and too little on the modeling. Models rarely agree on their data assumptions, use different levels of spatial and temporal aggregation, and use highly inflexible and restrictive data management techniques. Today, techniques such as GIS exist to handle such vast quantities of data. To do any comparative (or interactive) modeling, the data for the region needs to be stored for use in different models that require data at different scales and levels of accuracy in specific formats. An efficient method to do this is to create and maintain a GIS for the Great Lakes region that would not only have relevant GCM input data, groundtruth(s) and GCM prediction, but basin descriptors, model outputs, socio-economic data, etc. that can be stored, queried, graphically displayed, compared, interfaced with models, or otherwise analyzed.
- Research is needed into a sensible evaluation and statistical comparison of GCM model estimates of various variables both among themselves and with the groundtruth.

- There is a definite need to develop new approaches for inclusion of climate change effects in hydrology. Simple scaling of historical data for predicting future hydrology will not be sufficient for water resource planning decisions. The relative merits and disadvantages of various integrated or interacting climate change-hydrologic models should be studied in detail.
- There should be more research into the incorporation/interfacing of the important socio-economic effects into the hydrologic modeling approach. It is also necessary to further examine if there are any adaptive design implications of the hydrologic and other predictions.
- The Great Lakes region could be used as an important case study to test out a number of different hydrologic models and to test the differences in climate and hydrologic predictions by an integrated regional GCM-hydrologic model with those of global GCMs linked to hydrologic models.

BIBLIOGRAPHY

Blumberg, A. F., and Dominic M. DiToro, 1988, "The Effect of Climate Warming on Lake Erie Water Quality," HydroQual, Inc., Mahwah, N.J.

CEES, 1992, Our Changing Planet: The FY 1993 U.S. Global Change Research Program, A Report by the Committee on Earth and Environmental Sciences (CEES), Washington, DC., 79 pp.

Cohen, S.J., Great Lakes Levels and Climate Change: Impacts, Responses, and Futures, in Societal Responses to Regional Climatic Change: Forecasting by Analogy, Section II: Case Studies, Edited by M.H. Glantz, Westview Press, 1988.

Cohen, S.J., Impacts of CO_2 Induced Climatic Change on Water Resources in the Great Lakes Basin, Climatic Change 8, pp. 135-153, 1986.

Croley, T.E., II, Laurentian Great Lakes Double-CO2 Climate Change Hydrological Impacts, Great Lakes Environmental Research Laboratory, National Oceanic and Atmospheric Administration, GLERL Contribution No. 646, 1990.

Croley, T.E., II, Great Lakes Hydrological Impacts of $2xCO_2$ Climate Change, International and Transboundary Water Resources Issues, American Water Resources Association, GLERL Contribution No. 688, April 1990.

Croley, T.E., II and Hartmann, H.C., Climate Change Effects on Great Lakes Levels, Hydraulic Engineering '89 Proceedings, National Conference on Hydraulic Engineering/HY Div/ASCE, New Orleans, LA, August 14-18, 1989.

Fiering, M. B, and P P. Rogers, 1991, "Statistical Issues in Reservoir Allocation," Report to the Massachusetts Water Resources Authority and the U.S. Army Corps of Engineers (Draft).

Gleick, P. H., Spring 1990, Global Climatic Changes: A Summary of Regional Hydrological Impacts, Civil Engineering Practice, 53-57.

Hartmann, H.C., Climate Change Impacts on Laurentian Great Lakes Levels, Great Lakes Environmental Research Laboratory, National Oceanic and Atmospheric Administration, GLERL Contribution No. 645, 1990

Hartmann, H.C., Great Lakes Climate Change Contingency Planning, Great Lakes Environmental Research Laboratory, National Oceanic and Atmospheric Administration, 1990.

Hartmann, H.C., Climate Change Impacts on Great Lakes Levels and Flows: Energy and Transportation Implications in Climate Change: Implications for Water and Ecological Resources, An International Symposium/Workshop, sponsored by The Water Network, Canadian Climate Centre, Environment Canada, Sustainable Development Branch, Environment Canada, Canada Committee on Ecological Land Classification, The Grand River Conservation Authority, Waterloo Inn, Waterloo, Ontario, March 14-16, 1990.

James, I.C., B.T. Bower and N.C. Matalas, December 1969, "Relative Importance of Variables in Water Resources Planning," Water Resources Research, 5, 6, 1165-1173.

James, M., Pattern Recognition. BSP Professional Books: Oxford, England, 1987.

Jenne, R., Data from Climate Models; The CO2 Warming, Draft, August 26, 1988, Revised March 6, 1989.

Marchand, D., M. Sanderson, D. Howe and C. Alpaugh, "Climatic Change and Great Lakes Levels: The Impact on Shipping," Climatic Change. 12 (1988), 107-133.

Matalas, N.C. and M. Fiering, Water Resource Systems Planning, Chapter 6 in Climate, Climatic Change and Water Supply, Report of the Panel on Water and Climate, Studies in Geophysics, National Academy of Sciences, 1977.

Mearns, L. and S. Rhodes, Conference Organizers, Great Lakes Climate Change Impacts: Implications for Environmental Restoration, Interdisciplinary Climate Systems Section and Environmental and Societal Impacts Group, National Center for Atmospheric Research (NCAR), Report of a Workshop, 28-29 April, 1992.

Parry, M. L., and T. R. Carter, 1986, "Effects of Climate Change on Agriculture and Forestry: An Overview," in U.S.EPA, Effects of Changes in Stratospheric Ozone and Global Change, 1, 257-297.

Rind, D., C. Rosenzweig and R. Goldberg, 1992, Modeling the hydrological cycle in assessments of climate change, Nature, 358, 119-122.

Rogers, P., and M. Fiering, From Flow to Storage, Chapter 9 in Climate Change and

U.S. Water Resources, Paul E. Waggoner (Ed.), Report of the AAAS Panel on Climatic Variability, Climate Change and the Planning and Management of U.S. Water Resources, Wiley Series in Climate and the Biosphere, John Wiley & Sons, Inc., 1990.

Rosenberg, N.J., B.A. Kimball, P. Martin and C.F. Cooper, From Climate and CO2 Enrichment to Evaporation, Chapter 7 in Climate Change and U.S. Water Resources, Paul E. Waggoner (Ed.), Report of the AAAS Panel on Climatic Variability, Climate Change and the Planning and Management of U.S. Water Resources, Wiley Series in Climate and the Biosphere, John Wiley & Sons, Inc., 1990.

Rosenberg, N. J., *et al.*, 1990, "Processes for Identifying Regional Influences of and responses to increasing atmospheric CO_2 and Climate Change -- The MINK Project: Working Paper I, Background and Baselines," Prepared by Resources for the Future for Pacific Northwest Laboratory per Contract with U.S. Department of Energy, PNL, Richland, WA. 114 pp.

Schwarz, H. E., 1977, "Climatic Change and Water Supply: How sensitive is the Northeast?" Chapter 7 in The National Research Council, Climate, Climatic Change, and Water Supply, National Academy of Science.

Thomas, H. A., Jr., April 1971, "Sensitivity Analysis of Design Parameters of Water Resource Systems," Harvard Water Program, mimeo, 25 pp.

FIGURE 1
Socio-Economic Consequences of Climate Change

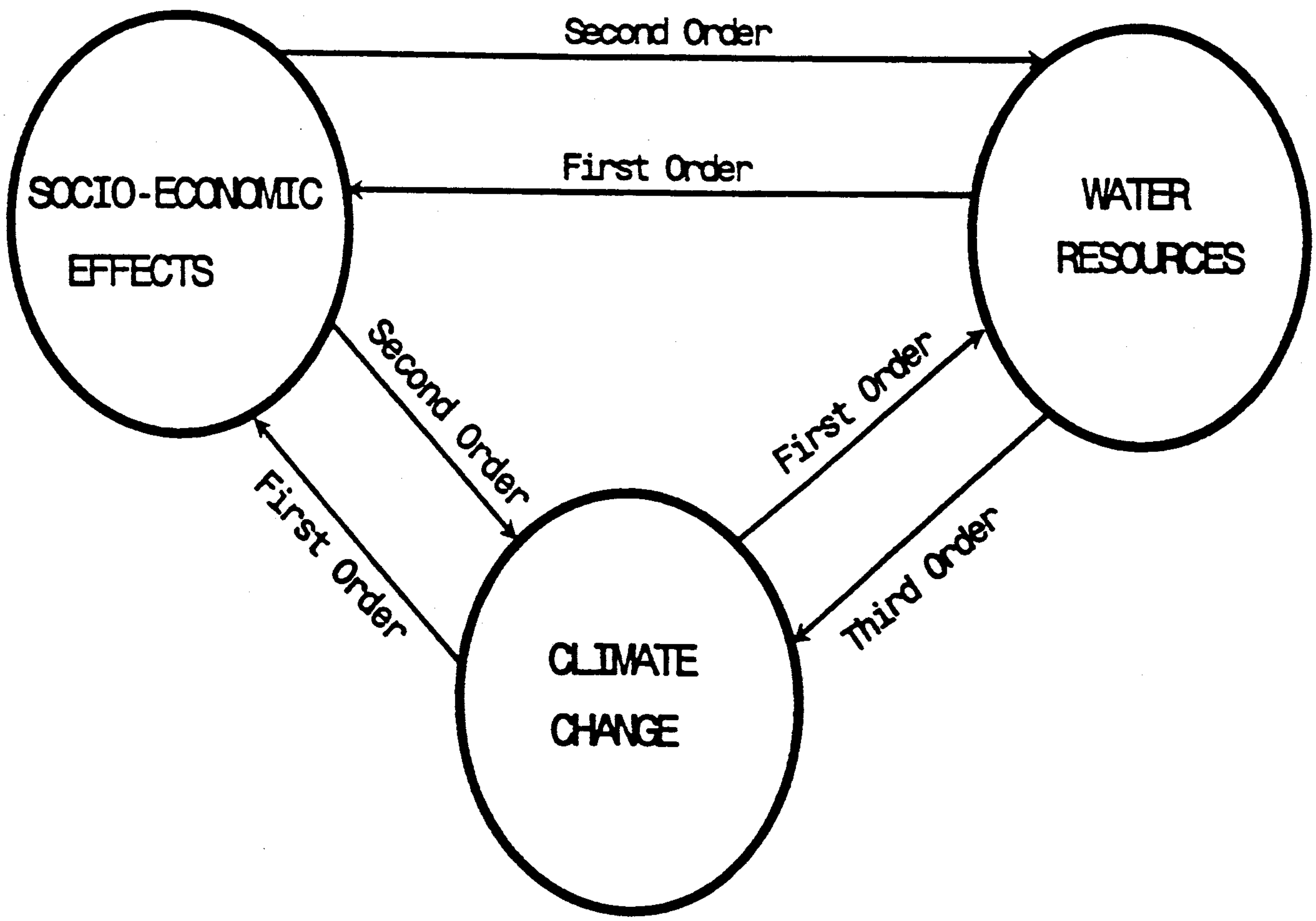
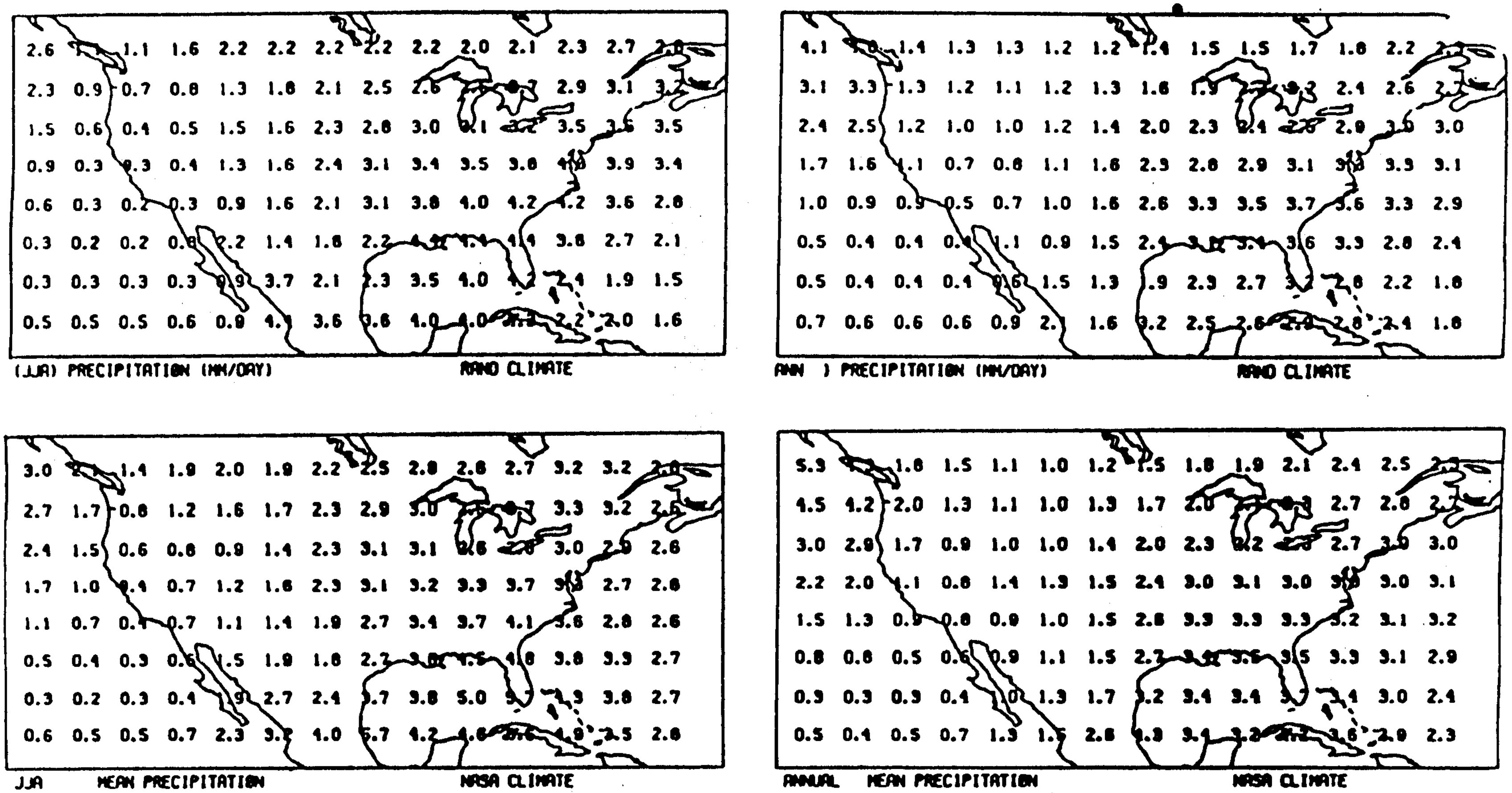


FIGURE 2

Difference between RAND and NASA climates



Comparison of two climatologies for precipitation during the summer and for the whole year. The Rand climatological tape uses data from Möller, 1951. The NASA tape has data from Jaeger, 1976. In this paper the "Rand" climate is used. The location of the number is just above the decimal point.

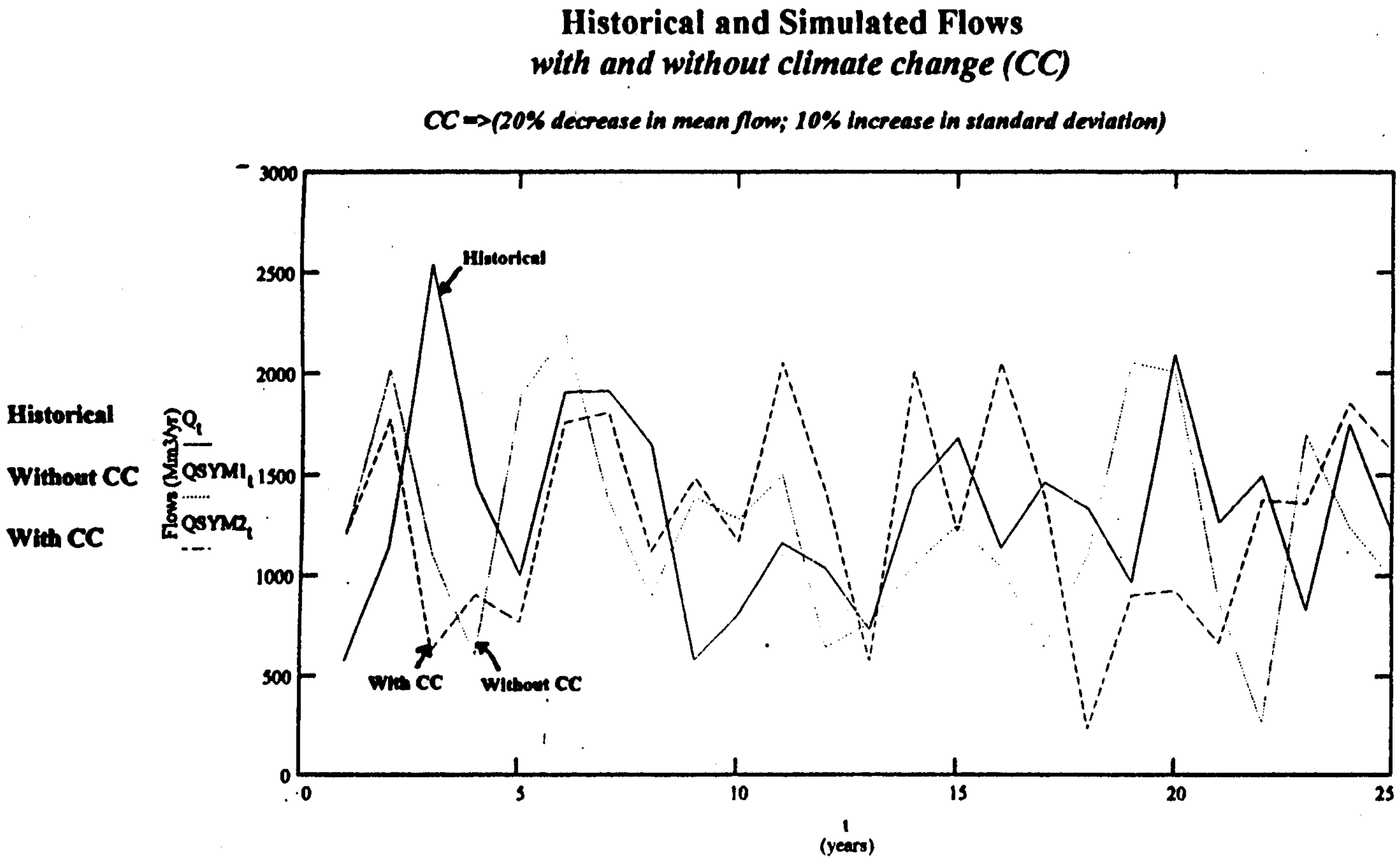
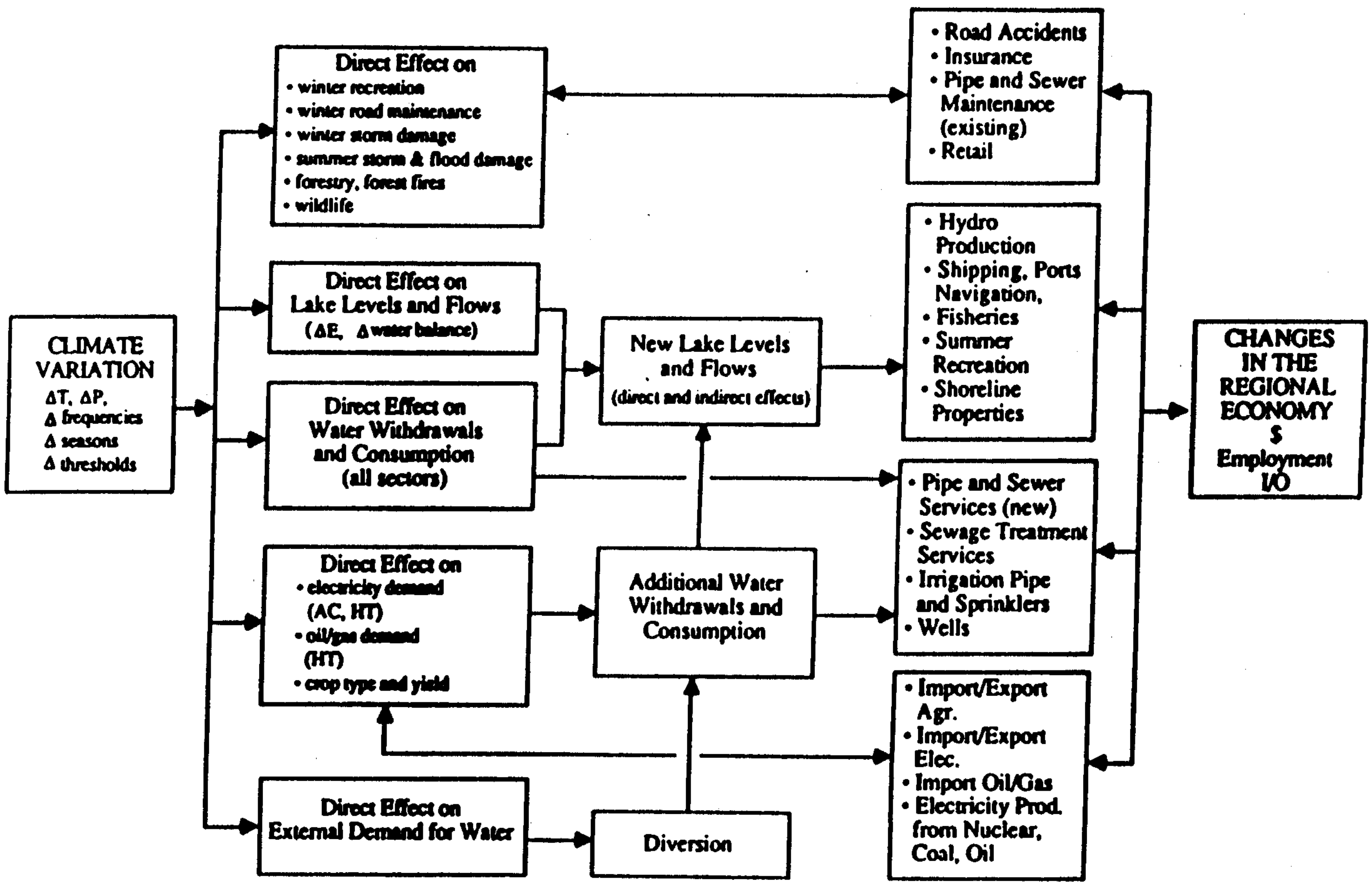


FIGURE 3
Stochastic Simulation Model with Climate Change

FIGURE 4
Climate Change Impacts on Great Lakes Basin

GREAT LAKES IMPACTS STUDY



Interconnected components of climate impacts and societal responses within the Great Lakes region. Δ = change, T = temperature, P = precipitation, E = evaporation, AC = air conditioning, HT = space heating, I/O = inputs/outputs. (Source: Cohen, 1986)

FIGURE 5
Temperature estimates of GISS: $1xCO_2$ vs. $2xCO_2$ Regression

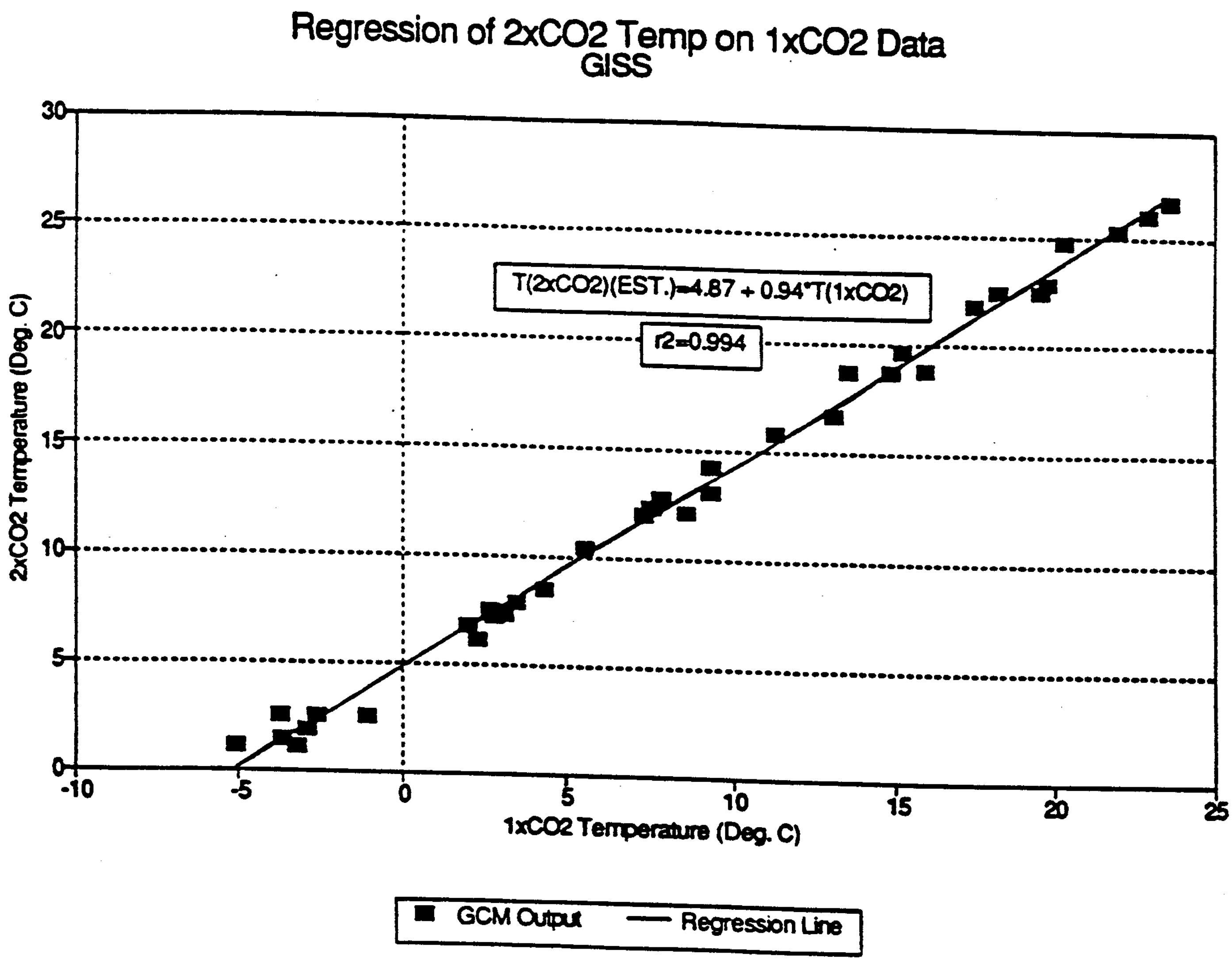
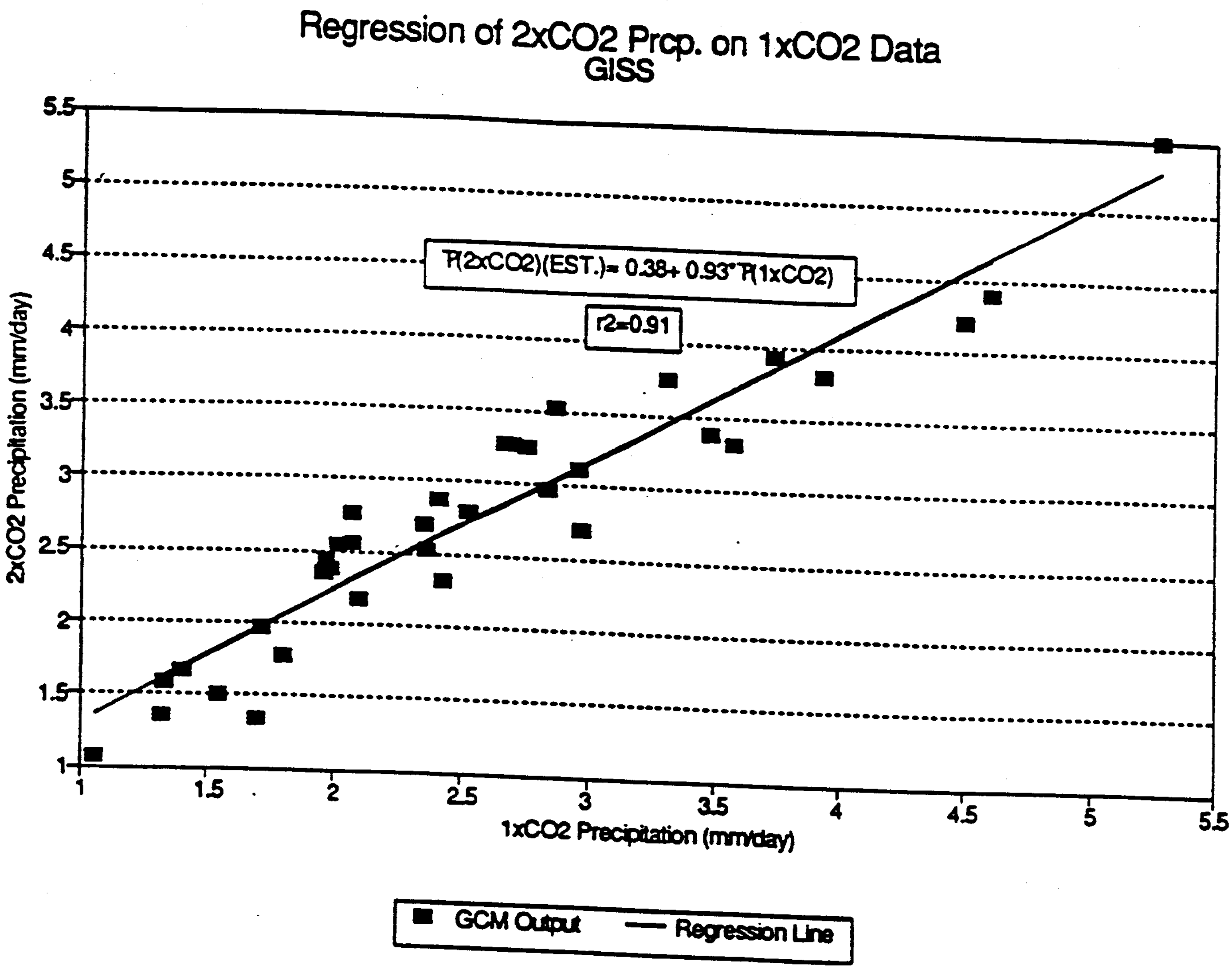


FIGURE 6
Precipitation estimates of GISS: $1xCO_2$ vs. $2xCO_2$ Regression



Great Lakes Global Climate Change: Implications for Water Policy and Management

by
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The freshwater resources of the Great Lakes basin provide the centerpiece of a rich and diverse natural ecosystem that plays a vital role in the regional and national economies of the United States and Canada.[1] From historical times until the present, these freshwater resources have not only influenced, but in many ways defined, the basin's environmental and socio-economic characteristics. The sheer magnitude of the resource has, over the years, fostered the perception that the Great Lakes system offers a virtually inexhaustible supply of fresh water that can accommodate all current and projected uses while exhibiting extraordinary resilience to anthropogenic stress. In reality, the system's water resources are finite, intensively used, and ecologically fragile. Even a modest adjustment in lake levels or a localized alteration in water quality can have pronounced and pervasive implications for basin residents.[2]

Even under the most conservative scenarios for global climate change, residents of the Great Lakes basin will experience changes in lake levels, average temperatures, and precipitation patterns that will bring about a gradual yet fundamental shift in the characteristics of the resource base and associated socio-economic activity.[3] Implications of this shift for water policy and management are profound. Despite the scientific uncertainty associated with the regional consequences of global climate change, policymakers must assume an anticipatory mode, formulating strategies to adapt to, mitigate, or otherwise minimize disruptions to the integrity of the resource and its socio-economic applications.[4]

Such strategies will entail a shift in patterns of water usage and, more fundamentally, in the legal and institutional underpinnings for present resource management practices. Ensuring that such a shift is effected in a studied, rational manner devoid of the political trappings of crisis response decision making may require decades of concerted effort.

In the following discussion, selected hydrologic and socio-economic characteristics of the Great Lakes resource will be introduced to highlight the public policy significance of the resource generally, and the climate change issue in particular. Findings and projections from general circulation models will be presented to illustrate both the direction and magnitude of projected change under various climate change scenarios. Several use sectors/characteristics of the resource will provide case studies for an examination of projected impacts, socio-economic consequences, and policy responses. Recommendations for action by regional leaders will then be presented, including policy elements for inclusion in a formal, federally-initiated Great Lakes climate change program.

The Great Lakes System and its Public Policy Significance

The binational Great Lakes system is one of virtually unfathomable expanse and corresponding complexity. Its myriad characteristics are inextricably linked to—and in large part the determinants of—the region's environmental health, economic well-being and overall quality of life. Yet, the expansiveness and complexity of the resource belies its fragility. Even minor stresses—whether they be physical, biological or political—can have lasting impacts upon the sustainable use, development and protection of the resource.

The Great Lakes system enjoys global prominence, containing some 6.5 quadrillion gallons of fresh surface water, a full 20% of the world's supply and 95% of the United States' supply.[5] Its component parts—the 5 Great Lakes—are all among the 15 largest freshwater lakes in the world. Collectively, the lakes and their connecting channels comprise the world's largest body of fresh surface water. They lend not only geographic definition to the region, but help define the region's distinctive socio-economic, cultural, and quality of life attributes as well.

An international resource shared by the United States and Canada, the system encompasses some 95,000 square miles of surface water and a drainage area of almost 200,000 square miles.[6] Extending some 2,400 miles from its western-most shores to the Atlantic, the system is comparable in length to a trans-Atlantic crossing from the east coast of the United States to Europe. Recognized in U.S. federal law as the nation's "fourth seacoast," the Great Lakes system includes well over 10,000 miles of coastline. The coastal reaches of all basin jurisdictions are population centers and the locus of intensive and diverse water-dependent economic activity. Almost 20% of the U.S. population and 40% of the Canadian population resides within the basin.

The role of the Great Lakes system in advancing and sustaining regional, national, and binational economic development has long been recognized. The physical presence, geographic configuration, biological diversity, and climatological characteristics of the lakes and their related land resources have been, and continue to be, determinants of locational decisions for business and industry.[7] Much of the early economic activity during settlement of the region was directly attributable to resource exploitation potential (e.g., fisheries, trapping, mining, forestry) and the availability of water-based transport. While the industrial base has diversified over the years, the basin's water resources continue to exercise a substantive role in the attraction, retention and day-to-day operation of industry. Every day, for example, over 980 billion gallons of water are withdrawn or used instream for industrial, municipal, agricultural, power generation and other purposes.[8] Every year, basin industry accounts for 70% of all U.S. steel production, 20% of U.S. heavy manufacturing, and 50% of Canada's heavy manufacturing.[9] The Great Lakes St. Lawrence Seaway contributes $3.0 billion annually to the region's economy.[10] The sport fishery is valued at $2.0-4.0 billion annually in direct and indirect benefits.[11] Economic activities as diverse as agriculture, recreational boating, and water-based tourism are all multi-billion dollar industries.

These various resource uses in the Great Lakes basin share two characteristics relevant to the issue and implications of climate change. All are highly dependent upon access to reliable sources of abundant and relatively high quality water. They are also highly sensitive to variations in the resource.[12] For the most part, water-based industries have become dependent on a small seasonal variation in lake levels, typically 12-24" in seasonal variation over the course of a year. Even a modest, gradual departure from long-term averages can translate into tens of millions of dollars in economic loss or benefit. For example, a prolonged one-inch reduction from the long-term average can translate into reduced hydropower capacity and can compromise the efficiency of interlake and ocean-going vessels that typically use every inch of dredged shipping channels. Conversely, modest increases in levels can—and have had—devastating effects on shoreline erosion, structures, and other property. Climate change scenarios suggest prolonged alteration of levels and flows; precipitation and evaporation patterns; air and water temperatures; biological diversity and composition; and all attendant population, socio-economic, legal/institutional, water usage and demand characteristics.

The climate change issue is also significant from a policy standpoint in that it may signal a departure from the time-tested crisis response decision making mode. The development, application, and critique of general circulation models has received a notable degree of attention to date, and policy implications have been discussed and acknowledged—albeit in cursory fashion—in water resource plans of various basin jurisdictions. Under the best circumstances, however, the active implementation of adaptive strategies is likely to be years away for any individual jurisdiction or the basin as a whole.

Climate change is an issue that has a multi-dimensional character and demands a multi-disciplinary, multi-jurisdictional response. It defies precise quantification, and is a case study of decision making under uncertainty, with both limited and sometimes contradictory information. The ability of the Great Lakes leadership to formulate and implement scientifically sound, socio-economically viable, and environmentally responsible policies of this type may well pave the way for enlightened public policy on other complex issues with similar characteristics.

Climate Change Projections and Impacts

In recent years, a number of climate change scenarios have been developed for the Great Lakes basin.[13] Many reflect the application and interpretation of three general circulation models based upon the assumption that carbon dioxide concentrations will double over pre-industrial levels by the middle of the next century. These include models of the Goddard Institute for Space Studies (GISS); the Geophysical Fluid Dynamics Laboratory (GFDL); and Oregon State University (OSU); all developed in the early to mid-1980s.[14]

In 1989, at the request of the U.S. Congress, the U.S. Environmental Protection Agency (U.S. EPA) used these three models as a basis for examining the potential impacts of climate change on health and environment in the United States. The Great Lakes was one of four regions of particular interest. The reliability and validity of all such models is particularly suspect on a region-specific basis, yet such applications can be useful in suggesting the likely direction and, to a lesser extent, the magnitude of change for different parameters. The U.S. EPA review did find substantial variability among the three models, although the direction of change was consistent. At the global level, for example, all indicate an increase in average air temperatures and annual precipitation. In the Great Lakes basin, U.S. EPA-commissioned studies derived from these models suggest, among others, lowered lake levels, reduced ice cover, a lengthened shipping season, increased shipping and dredging costs, adverse water quality impacts including reduced dissolved oxygen levels, and increased fish productivity.

A brief discussion of anticipated climate change impacts on these and other hydrologic characteristics/resource uses follows:

- Lake Levels: Although projections vary from one model to the next, it is generally agreed that the doubled carbon dioxide scenario will lead to a precipitous drop in average lake levels, due to higher air temperatures, an attendant reduction in the snowpack, and an increase in evaporation. Levels may be lowered from .4 to 2.5 meters, depending upon the lake, according to NOAA's Great Lakes Environmental Research Laboratory (GLERL).[16] Historic lows would be experienced for Lakes Michigan, Huron, and Erie.

- Ice Cover: Research at GLERL has found that Great Lakes ice cover would be significantly reduced under a doubled carbon dioxide scenario.[17] While a climate change-induced reduction in wind speed may temper the impact, these findings point to the virtual disappearance of ice cover from central and eastern Lake Erie, and a substantial reduction in Lake Superior, likely from 4 to 1 1/2 months per year.

- Shipping: Climate change impacts are mixed for waterborne transportation. Reduced ice cover will extend the shipping season, while lower average lake levels will limit cargo capacity, require substantial increases in dredging activity in ports and connecting channels, and necessitate infrastructure adjustments (e.g., docks, water supply sources).[18, 19, 20]

- Water Quality: The higher average annual water temperatures associated with various climate change scenarios are expected to lead to accelerated eutrophication.[21] Changes in the thermal structure of the lakes (particularly areas such as Lake Erie's central basin) will include prolonged stratification and attendant dissolved oxygen problems. Warmer surface temperatures may keep the Lakes from thoroughly mixing each year, affecting the mixing of nutrients. Lowered levels, coupled with nonpoint source pollution in the form of urban and agricultural run-off, suggest the possibility of exacerbated nearshore water quality problems due to increased concentrations of contaminants. Also, exposure of toxic substances in present-day wetlands is a concern.

- Biological Diversity: The impact of climate change on biological diversity is more a matter of speculation than interpretation of research. However, it is recognized that lower average lake levels may cause a decline in the number and size of estuaries and wetlands, reducing spawning and breeding grounds for fish and waterfowl.[22] Attendant water quality problems, noted earlier, will be a factor as well. Climate conditions will shift ecological regions northward, and the resultant change in agricultural and forestry characteristics—as well as development, population and industrial patterns—will affect both the viability and migration of current plant and animal species, and the influx of non-indigenous species that may compete with established species. As one example, warmer average water temperatures would likely accelerate the spread of zebra mussel populations and exacerbate their adverse impacts on native clams and their disruption of the food chain.

- Agriculture: Benefits associated with climate change scenarios for the Great Lakes includes a longer growing season, an extension and shift of crop ranges that may increase viable agricultural acreage in the basin, and the possibility of higher crop yields due to increased rates of photosynthesis in some species.[23] Adverse impacts include an increase in the activity and geographic range of unwanted insects and plants that prey on or compete with crops, suggesting the potential for increased usage of herbicides and pesticides. Increased evaporation suggests lowered soil moisture and yields, likely prompting a pronounced increase in irrigation activity.

- Fisheries: As with agriculture, research into the projected impact of climate change on the Great Lakes fishery yields mixed results.[24] Higher water temperatures will accelerate phytoplankton and zooplankton production, lengthen the growing season and, for many species, expand the thermal habitat. On the other hand, the higher metabolism associated with fish in warmer weather may increase competition, placing pressure on the forage base. Summer habitat could actually be reduced due to dissolved oxygen problems. Further, as noted earlier, such changes are likely to promote the introduction and spread of aquatic nuisance species such as the zebra mussel.

The Policy Implications of Climate Change

The policy implications of climate change in the Great Lakes basin are appropriately examined at two levels. The first level entails a sector-by-sector examination of water use activity to determine specific impacts and the associated policy responses/implications for that activity. This approach is fairly straightforward and intuitive, at least on a qualitative basis. For any given sector of water use activity, there is likely to be both positive and negative impacts, and the relative magnitude of each will help shape and define the debate over the nature of the appropriate policy response. For example:

- A climate change-induced lowering of water levels—at least to a point—would likely be welcomed by riparians who have endured years of shoreline erosion, flooding and property damage. On the negative side, adverse impacts are noted for hydro-electric power generation efficiency, impediments to commercial and recreational navigation, alteration of nearshore aquatic habitat, alteration of coastal development pressures and patterns, and reduced access to water resources for instream or withdrawal purposes. The policy decision involves lake regulation. Can lake regulation plans currently maintained by the International Joint Commission accommodate projected impacts on lake levels of climate change? How will tradeoffs among competing resource users best be handled? How should anticipated impacts on lake levels be addressed by state\provincial coastal zone management plans, zoning ordinances, and other land use policies?

- Ice free or reduced ice conditions will lengthen the navigation season, but reduced cargo capacity and increased maintenance dredging costs will affect the viability of Great Lakes transportation. At what point, if any, will the economic costs and environmental implications of such dredging outweigh the benefits of maritime transportation vs. other modes? Who should pay for the increased costs, and where should the contaminated dredge materials be deposited?

- Climate change impacts point to pronounced near shore water quality problems, and increased sensitivity to both point source discharges and urban and agricultural runoff. Will existing standards need to be strengthened to ensure acceptable water quality? Will urban and agricultural land use practices need to shift from largely voluntary compliance to a regulatory mode? What compliance costs will accrue to business and industry, and will those costs outweigh the benefits of access to Great Lakes water?

- Higher average water temperatures will promote fisheries production, but the range and mix of species will be altered. If such a scenario is inevitable, how will near and long-term fish stocking programs be affected? Should strategies for the control of aquatic nuisance species such as the zebra mussel and ruffe be redirected, enhanced or altogether terminated? Should prevention strategies now be implemented for aquatic nuisance species that cannot presently thrive in the Great Lakes, but could with higher average water temperatures?

- The loss of biological diversity and compromised viability of rare and endangered wildlife and vegetation species is a consequence of climate change. Should our policy approach entail managing the ecosystem to remain in its current state, or to ease its transition to a new state? Should habitat enhancement/wetlands creation programs be accelerated in anticipation of the loss of present wetlands? Should current endangered species protection programs be enhanced, or abandoned on the basis of their inevitable failure due to climate change effects?

- The quality of human health will be affected to some degree under any climate change scenario, given the existence of climate-related ailments, the likely anticipation of exposure pathways to concentrations of toxic chemicals, and overall changes in air and water quality. What is the magnitude and direction of anticipated human health impacts? Are they significant enough to warrant extensive research, perhaps at the expense of other human health research priorities? What adaptive responses (e.g., immunizations, disease control) may be required, and at what cost to society and the individual?

That is but a modest sampling of the issue/sector-specific policy questions that arise when climate change is introduced as a variable in the long-term planning process. To pose a further challenge, however, is a second level of anticipated impacts and policy responses that transcend the boundaries of any single water use issue or sector. At this level, questions of regional and international significance arise that challenge the very foundation upon which Great Lakes water resource policy has historically been based. Three issues are of predominant concern:

- Climate change scenarios are not Great Lakes-specific; they will reduce water supplies and profoundly effect water usage patterns in non-basin areas as well. The impact will be particularly severe in areas, such as the southwestern United States, that have long been plagued by extended droughts and dependent upon inter-basin transfer for adequate water supplies. One inevitable consequence is increased pressure for diversions from water-rich regions such as the Great Lakes. Further, low water crises conditions may generate political pressure for diversions into the basin; such as the Grand Canal scheme so vehemently opposed in years past. Inter-regional conflict over water diversion, fueled by a real or perceived crisis and past federal court rulings defining water as an article of interstate commerce, will escalate. A political showdown within the U.S. Congress, pitting an embattled Great Lakes Congressional Delegation (with reduced member since the 1990 census redistricting) against a growing southwestern states delegation is a likely scenario. The latter delegation will enjoy the support of other regions that may wish to keep their options open should climate change impacts adversely affect their own water supplies.

It is also likely that the spirit of cooperation and common purpose shared by Great Lakes jurisdictions will be severely tested under climate change-induced water shortages. Recent intra-regional diversion proposals [e.g., Pleasant Prairie (WI), Lowell (IN), Mud Creek (MI)] subjected to the prior notice and consultation process of the 1985 Great Lakes Charter have raised questions concerning the viability of that process, and have strained interstate relations.[25]

In sum, climate change impacts on water supply and availability will exacerbate inter and intra-regional conflict and competition. The nature, profile, complexity, and consequence of water resource policy and management in the Great Lakes basin will be elevated accordingly.

- The philosophical and legal basis of Great Lakes water policy is not one of managing for scarcity and attendant conflict, but one of managing for abundance and, at times, overabundance.[26] The basin's entire institutional infrastructure, policy framework, and programmatic orientation reflects this fact. Unlike states in water-scarce regions of the country, Great Lakes jurisdictions (with limited exceptions in some localities) lack the legal framework or administrative structure to allocate water supplies, monitor use, employ real-cost pricing mechanisms, implement conservation practices, or consider water availability and usage as a factor in growth management planning.

The basin's legal and institutional infrastructure, like the resource user community in general, has evolved on the assumption that lake level/water availability—both seasonally and over the longer term—will vary in a modest and reasonably predictable way. This infrastructure exhibited signs of severe stress during the high lake level years of 1986-87 and, in its current configuration, can be expected to endure a similar degree of stress under low level conditions.

Policy deliberations associated with climate change impacts in the Great Lakes basin must not regard the current legal institutional framework as either untouchable or immovable. Its ability to facilitate—or propensity to impede—adaptation to climate change impacts must be assessed. If the latter is the case, a fundamental revision to—or outright rejection of—this framework must be considered. The magnitude of such a task must not be underestimated, as decades may be required to effect the transition to a new framework.

- The policy response to climate change will not be limited to governments alone; impacts will ultimately affect all basin residents. Issues of water availability and environmental quality are important factors in locational decisions for business and industry, and are central to quality of life expectations of basin residents.[27] Migration and settlement patterns of current and future basin residents will be affected by changing socio-economic conditions brought on by climate change. Conflicts among resource users competing for once plentiful water supplies will increasingly be played out in the courts. The prospective implementation of mandatory water conservation practices or related resource use restrictions will have widespread behavioral change implications. Given these many and varied implications for those who live and work in the Great Lakes basin, the acceptance and ultimate success of any adaptive strategy must be grounded in a strong partnership among all basin stakeholders.

Options for a Policy Response

Many options are available when developing a public policy response to climate change. These can range from outright rejection of the theory itself to prompt and concerted action on the basis of the "worst case" scenario. The imprecision of current general circulation models accounts for the diversity of public policy perspectives at this time; the models do have limitations.[28] Their projections are uncertain and cannot be verified; their accuracy at a basin-specific level is suspect; their reliability is greater on a latitudinal as opposed to longitudinal basis; and they embrace many assumptions concerning current and future climate variability. As a consequence, they are most appropriately viewed as vehicles for describing various likely future scenarios, rather than outright predictions.

It is useful, for discussion purposes, to describe three prospective policy responses, recognizing that many variations exist.[29, 30] The strengths and weaknesses associated with each are briefly identified in the following discussion, and a preferred approach is subsequently offered.

The first such option discourages the development and implementation of any adaptive strategy until further research confirms the legitimacy of climate change concerns, and yields reasonably defensible estimates of the magnitude and direction of change. Once consensus is reached within the scientific community, a strategy can be designed with confidence, and the strength of the scientific evidence would presumably generate the political will and public support required for successful implementation.

The current state of scientific inquiry and model development suggests that achieving this degree of certainty may be many years, or even decades, in the future. The gestational period for policy development, and the attendant large scale legal and institutional revisions that may need to accompany it, is a lengthy one. Many argue that this policy option, while laudable in concept, would cause an inordinate delay in adaptive actions.

A second option is the antithesis of the first; a worst case scenario is assumed and a policy response is immediately and aggressively pursued. Adaptive and mitigative efforts are implemented on a regional and, to the extent possible, a global scale. Associated voluntary and mandatory actions would profoundly affect established socio-economic patterns and behaviors.

In theory, such decisive action holds great promise in arresting climate change trends and/or facilitating societal adaptation to them. In reality, the risks are substantial, given scientific uncertainty over the magnitude and direction of climate change, associated impacts, and the effectiveness of mitigative actions. Further, the likelihood of strong political support for drastic actions (e.g., phasing out the use of fossil fuels, halting deforestation) is limited on a national level, and highly doubtful on multi-national or global level.

A third option is commonly known as the "no regrets" policy, and is best characterized as a moderate initiative on the continuum of public policy options. This policy calls for prompt implementation of actions considered to be reasonable and appropriate irrespective of uncertainties associated with the climate scenarios that prompted them. Such actions can correct known environmental problems (e.g., deforestation, fossil fuel over-dependency, air deposition, water pollution) and, in so doing, contribute to the resolution of, or adaptation to, any climate change scenario that may eventually be validated.

The "no regrets" policy provides for immediate action, but avoids directing massive resources to a problem that may not be verified for many years, if at all. It does target "sub-problems" that contribute to climate change and, in so doing, can attain measurable results over the shorter term. It does not, however, provide the concerted, large scale action that might (in retrospect) be needed if the worst case climate change scenario becomes a reality.

Pursuing a "No Regrets" Policy: Recommendations for Action

Despite limitations and uncertainties associated with climate change projections for the Great Lakes basin, the argument for a "no regrets" policy is a compelling one. The weight of evidence in scientific inquiry indicates that global warming is, in fact, occurring. General consensus on the direction of change has been reached, while the magnitude of that change is a matter for continuing inquiry. Within the Great Lakes basin specifically, the sensitivity of the physical system and its socio-economic characteristics to even modest climate variability is well documented. Further, it is recognized that any fundamental adjustment to or rebuilding of the basin's complex legal and institutional infrastructure may require years—if not decades—to accomplish. Preventive and adaptive policies can be implemented in the near term on the basis of present knowledge, despite the aforementioned uncertainties. At the minimum, such policies can make an important contribution by advancing the state of ecosystem management, even if climate change projections are determined to be less ominous than they now appear. If "worst case" projections are validated, such policies will have set in place a solid foundation for more aggressive measures.

Operationalizing a "no regrets" policy entails a multi-faceted approach. It requires an enhanced commitment to basic and applied research in the future. It calls for an assessment of past and present research, through a weight of evidence approach, to distill and apply policy-relevant findings. It demands political leadership to ensure that such findings are incorporated into the resource planning and management practices of public entities and private interests over the long term. Finally, it provides a foundation on which to build, should future scientific inquiry yield a compelling rationale for markedly different policy, planning, and management strategies. Over the short term (i.e., one to five years), a number of specific initiatives can be undertaken to operationalize a "no regrets" policy. Six such initiatives—or policy elements—are offered below.

First and foremost, political leadership in the Great Lakes basin must acknowledge—publicly and forcefully—that scientific certainty is not an absolute precondition to formulating and implementing adaptive strategies. Anticipatory planning and action must replace long standing traditions of crisis response. Strong and sustained political leadership at the basin, national, and international levels can provide the mandate, financial resources, and public profile needed for aggressive and well-coordinated programs.

Second, it is imperative that Great Lakes political jurisdictions—states and provinces in particular—establish a watershed-based approach to managing the Great Lakes and their related land resources. A Great Lakes Charter was signed with much fanfare in 1985 by the Great Lakes governors and premiers in the name of informed, responsible, and consistent water resource management. [31] The development of a Great Lakes Water Resource Management Program was endorsed but never pursued. Despite an elaborate institutional infrastructure and history of interjurisdictional collaboration, a single, comprehensive plan for collecting and analyzing basin water use data is lacking, along with detailed procedures for addressing water use conflicts, diversion threats, lake level fluctuations, and the like. Establishing such a program over the shorter term will provide the foundation needed for implementing elements of a "no regrets" policy.

As a third initiative, Great Lakes political jurisdictions and their leaders must seize every opportunity to factor climate change into existing programs, policies, and agreements. The recently completed Levels Reference Study of the International Joint Commission is a good example; climate change issues were factored into lake level projections and policy recommendations.[32] The next renegotiation of the U.S.- Canada Great Lakes Water Quality Agreement may provide another opportunity.[33] At the U.S. federal legislative level, future Clean Water Act and Coastal Zone Management Act amendments should ensure that climate change issues and uncertainties are reflected in decision-making processes. Such an "infusion" strategy can be undertaken at all levels of government, as well as in corporate planning activities.

Elevating the Great Lakes basin to a prominent international position in climate change dialogue and decision-making is a fourth initiative that should be taken in the short term. At the regional level, many public officials, leading scientists and regional constituencies agree that the Great Lakes basin would serve as an ideal case study for quantifying climate change effects and assessing potential adaptive/mitigative strategies. This message must be conveyed at the national and international levels and to leading global climate change inquires such as those of the International Geosphere-Biosphere Program and the Intergovernmental Panel on Climate Change. Gaining such stature will prompt concerted attention at the regional level.

Fifth, a thorough and fundamental assessment of the basin's legal and institutional infrastructure for water resource planning and management is in order. The region's policymakers, and citizens in general, must be assured that this infrastructure will facilitate—rather than impede—the scientific inquiry, policy development, and decisionmaking processes necessary to respond to the issues and uncertainties associated with climate change. As noted earlier, the current infrastructure evolved over many decades, during which the challenge entailed managing for abundant and over-abundant water supplies as opposed to managing for scarcity and competing/conflicting uses. It is possible that existing authorities for regional, multi-jurisdictional agencies may require enhancement to meet emerging basin needs. A legal/institutional analysis would also be a valuable pre-cursor to the development of the aforementioned Great Lakes Water Resource Management Program.

Finally, it is imperative that a formal U.S.-Canada climate change program be established to provide an integrated approach to scientific inquiry and policy development directed at the binational Great Lakes basin. Current efforts of NOAA's Great Lakes Environmental Research Laboratory and Environment Canada's Atmospheric Environment Service to develop such a program warrant the full support of political leadership in both countries. Objectives of the program should, at the minimum, include those already established under Canada's existing Great Lakes-St. Lawrence basin Project on Responses to the Impacts of Climate Change and Variability.[34] It is essential that such a binational program maintain an active commitment to the development, implementation, and ongoing evaluation of specific policies and mitigative/adaptive strategies.

Notes

1. Federal Reserve Bank of Chicago and Great Lakes Commission (1991). The Great Lakes Economy: Looking North and South. Chicago, Illinois. 163 pp.

2. Levels Reference Study Board, International Joint Commission (1993). Levels Reference Study-Final Report. Submitted to International Joint Commission, Ottawa, Ontario and Washington, D.C.

3. Quinn, Frank H. (1992). "The Sensitivity of Water Resource Management to Climate Change: A Great Lakes Case Study." Great Lakes Environmental Research Laboratory, National Oceanic and Atmospheric Administration. Ann Arbor, Michigan. 13 pp.

4. Donahue, Michael J. (1992). "Climate and Global Change: The Responses and Policy Issues Related to Climate Change in the Great Lakes basin." Presentation to: American Association for the Advancement of Science, February 11, 1992. Chicago, Illinois.

5. Donahue, Michael J. (1987). Institutional Arrangements for Great Lakes Management: Past Practices and Future Alternatives. Chapter Two: "The Great Lakes Ecosystem: Placing the Physical Resource and Management Framework in Perspective." Michigan Sea Grant College Program, MICHU-SG-87-200T. Ann Arbor, Michigan.

6. Great Lakes basin Commission (1979). Great Lakes Fact Sheets. Ann Arbor, Michigan.

7. Schenker, Eric, H.N. Mayer and H.C. Brockel (1976). The Great Lakes Transportation System. University of Wisconsin Sea Grant College Program. Technical Report 230. Madison, Wisconsin.

8. Great Lakes Commission (1993). Annual Report of the Great Lakes Regional Water Use Data Base. Ann Arbor, Michigan.

9. Supra Note 5.

10. St. Lawrence Seaway Development Corporation (1984). "The Seaway." Seaway Review, July-August.

11. Talhelm, Daniel R. (1981). Current Estimates of Great Lakes Fisheries Values: 1979 Status Report (1981 Update). Great Lakes Fishery Commission, Ann Arbor, Michigan.

12. Supra Note 3.

13. Ohio Sea Grant College Program (1991). Global Change in the Great Lakes: Scenarios. NA90AA-D-SG496, project E/AID-2. Columbus, Ohio.

14. U.S. Environmental Protection Agency (1989). The Potential Effects of Global Climate Change on the United States. Report to Congress, J.B. Smith and D.A. Tirpak, eds. EPA-230-05-89-050. Washington, D.C.

15. Supra Note 14.

16. Croley, Thomas E. II (1990). "Laurentian Great Lakes Double CO_2 Climate Change Hydrological Impacts," Climate Change 17:27-47.

17. Assel, R.A., C.R. Snider, and R. Lawrence (1985). "Comparison of 1983 Great Lakes Winter Weather and Ice Conditions with Previous Years." Monthly Weather Review, Vol. 113.

18. Supra Note 14

19. Canadian Climate Program Board (1991). "Climate Change and Canadian Impacts: The Scientific Perspective." Prepared for Climate Change Digest, Atmospheric Environment Service, Environment Canada. 30 pp.

20. Koshida , Grace and B.N. Mills (1993). Climate Sensitivities, Variability and Adaptation Issues in the Great Lakes-St. Lawrence basin: A Reference Document (Draft). Atmospheric Environment Service, Environment Canada, Downsview, Ontario. 43 pp.

21. Supra Notes 14, 19 and 20.

22. Ohio Sea Grant College Program (1991). "Will Biological Diversity in the Great Lakes Region Suffer?" Scenario #2 in Global Change in the Great Lakes: Scenarios. NA90AA-D-SG 496, project E/AID-2. Columbus, Ohio.

23 Supra Notes 13, 14, 19 and 20.

24. Supra Notes 13, 14, 19 and 20.

25. Injerd, Daniel (1993). "Managing Great Lakes Water Diversion: A Diversion Manager's Viewpoint." Buffalo Environmental Law Journal. Fall, 1993. Vol. 1, No.2 pp. 299-305. Buffalo, New York.

26. Supra Note 5.

27. Great Lakes Commission (1992). Liquid Asset: Great Lakes Water Quality and Industry Needs. Ann Arbor, Michigan.

28. Supra Note 20.

29. Trefil, J. (1990). "Modeling Earth's Future Climate Requires Both Science and Guesswork." Smithsonian, 21(9):29-37.

30. Ohio Sea Grant College Program (1991). "Understanding Climate Models." Introduction to "Global Change in the Great Lakes: Scenarios. NA90AA-D-SG496, project E/AID-2. Columbus, Ohio.

31. Council of Great Lakes Governors (1985). Great Lakes Charter. Madison, Wisconsin.

32. Supra Note 2.

33. International Joint Commission (1972). Canada-United States Great Lakes Water Quality Agreement. (Amended in 1978 and 1987). Great Lakes Regional Office. Windsor, Ontario.

34. Canadian Climate Centre (1991). A Canadian Proposal for the Great Lakes-St. Lawrence basin Project on Responses to the Impacts of Climate Change and Variability. Atmospheric Environment Service, Environment Canada. Downsview, Ontario. 13 pp.

6.2 WATER POLICY AND MANAGEMENT BREAKOUT GROUP PARTICIPANTS

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Charles Southam, Environment Canada

6.3 BREAKOUT GROUP REPORT

Five Year Research Plan and Products:

(Plan should be developed with a bi-national and international approach)

1. Problem Definition (Technical, policy, and communication)

    -status of climate change
    -include data base
    -identify critical issues
    -"state of Great Lakes" series of reports, reassess on a regular basis

2. Communication (for all products)
    - plans for communication (fact sheets, visuals, strategy)

3. Decision Process Road Map

    -methodology (What decisions can we make now vs. later?)
    - set of "minimal regret" policies to be implemented now
    - evaluate adaptive/mitigative measures

4. Analysis of Institutional Arrangements

    -state/provincial
    -basin wide

5. Develop Climate Change Scenarios

-probabilities/sensitivities
-site and lake specific

6. Great Lakes Water Resource Management Program - Include climate change issues in decisions.

Critical Issues: (underlying all issues are data and information need issues)

1. Problem Definition/Analysis

-model risks, possibilities for future
-what is the problem? Is there a problem with climate change? Does it make any difference re:climate change?
- focus on future decisions, climate impacts that affect decisions for next decade. What are those decisions?
- consider how changes are evaluated. Perceptive v. real world problem (regional, national, international)
-identify present indicators of climate change, if any
-ID threshold points at which adaptive measures implemented
-no regrets concept
-long term v. short term
- What are cause-effect linkages?

2. Communication

- public/decision makers don't believe climate change is a priority
- how communicate info effectively to public, decision makers
- confidence limits/uncertainty
-public understanding, buy in to issue

3. Policy Issues

-Canada/U.S. question, coordination?
- jurisdictional/institutional arrangements: can they handle it? GL as source of water, problem for future, differences between lakes.
- interbasin transfers
- future decisions - climate impacts that affect decisions for next decade. Develop contingencies (Low probability, high consequence); adaptive responses; information/knowledge
- industry/environment balance
- impact of variability on management

4. Technical Issues

-detection: when will we know climate change has occurred?
-good data for all categories.
-simpler, more interactive models, accessible to decision makers and public.
-Sustainability and carrying capacity of systems, what do we have now?
- translate CGM outputs to all (hydrologic, temp, etc.) impacts.
- Lack of consistent, high quality data. Protocols for data collection "noise".
- Water quantity/quality interactions. (i.e., pollutant loading, nonpoint source pollution, etc.).
- look at quality of GCM data before proceeding.
- need consistent data base.

Research Objectives:

1. "Good science"

2. Evaluation/Feedback

3. Interdisciplinary/Integrative Approaches

Program Components:

1. Flexibility (incorporate variability)

2. Program Design (nuts and bolts--budget, staff etc.)

3. Define data needs

4. Evaluation tools

5. Define "hard science" issues

6. Protocols

Issue areas: diversion, demand, wetlands, shoreline, navigation, fisheries, water quality, infrastructure.

Products:

1. comprehensive understanding of issue - now and with further work (public and decision makers).

2. Database - uniform, multidiscipline, software available, groundtruths, predictions on GIS.

3. Simpler, interactive, integrated and flexible modeling approaches.

4. Adequate QA/QC protocols, set appropriate timeframes. ID and evaluate current data.

5. Project design- product is the 5 year plan. Problem analysis, assessment framework.

7.0 SYSTEM INTEGRATION/DATA MANAGEMENT

7.1 ISSUE PAPER

Integrated Assessment of Climate Change: Challenges Ahead

By

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Abstract

Integrated assessment is a trendy phrase that has recently entered the vocabulary of folks in Washington D.C. and elsewhere. The novelty of the term in policy-analysis and policy-making circles belies the longevity of this approach in the sciences and past attempts at their application to policy issues. This paper is an attempt at providing an overview of integrated assessment with a special focus on policy motivated integrated assessments of climate change. Different people may have different conceptions of what it means. This will be reviewed in Section Two where a taxonomy of models is presented. In Section Three of this paper I present an overview of the integrated assessment project at Carnegie Mellon. Our motivation is to inform the policy making process and address research prioritization. In order to achieve this goal, uncertainties in our knowledge need to be quantified and propagated through models. Much of this section is devoted to a discussion of the interplay of uncertainty and the design of integrated assessment models. Section Four provides a glimpse at the challenges ahead in the science which provides the foundation for integrated assessments, the integrated assessment methodologies, and our ability to produce useful information for policy decision-makers. Some broad conclusions are reflected in the final section.

1. Introduction

The climate change issue is complex and multi-faceted. There are probably as many objectives defined by the researchers as there are facets. For example, energy-economists have concentrated on implications of CO_2 abatement on the energy sector. A subgroup within these, (electric utility researchers) have explored the impact of climate change on their industry's long-term investment and operation decisions. Agricultural economists have attempted to quantify the impacts of climate change for key agricultural regions and activities. Ecologists and biologists have explored the impact of climate change from pole-ward migration of ecosystems to the CO_2 sensitive receptor-neurons in insects. Climatologists have attempted to predict future climates providing a canvas for impact assessments to paint all sorts of pictures.

The public policy challenge is none of these in particular and needs all of these in general. Two clear objectives can be defined for public policy makers. First, they need to learn what is known about climate change, its impacts, and the consequences of their policy actions. Second, they need to prioritize future policy motivated research to better inform such decision-making. Integrated Assessments (possibly of different designs) can be used to address both these needs.

2. Integrated Assessments for Climate Policy Evaluation

A number of policy motivated integrated assessments of climate change are underway. Each of these includes one or more of the following elements:

- Emissions and economic/social developments.
- Abatement (costs and efficiency).
- Climate change and impacts (trends and variability).
- Valuation of impacts.
- Adaptation to impacts (costs & efficiency).
- Geoengineering (costs & efficiency).

It is inappropriate to treat integrated assessments as if they were the analytical equivalent of Swiss Army knives. A consistent set of objectives need to be defined before an integrated assessment model can be developed. For example: should a cost-effectiveness or cost-benefit framework be developed?; should all four categories of policy choices (identified above) be considered?; should the model calculate an optimal strategy?; should the model be used as a pedagogical tool?; how transportable (across computation platforms) should the model be?; should the model address the issue of value of information and research prioritization?; etc. Various research groups have adopted different lists of desiderata, and their models reflect this diversity.

A simple taxonomy of models is presented in Table 1. This is by no means a complete review of all models used to address the climate change problem. The models reported are chosen as being representative of a particular approach to problem structuring. This taxonomy is based on the decision-framing of the models. The three categories of models are those where policies are chosen on: i) the basis of cost-effectiveness, ii) the basis of a limit to acceptable physical impacts (or a tradeoff between abatement costs and physical impacts), and iii) the basis of a cost-benefit framing.

Only the development of cost-benefit models demands that the dynamics of social and natural systems be represented within an integrated framework of assessment. This does not nullify the value of cost-effectiveness and cost-impact models. Indeed, if criteria for past policy decision-making are a guide (especially in the U.S.), the decision to protect environmental quality have never been based on a cost-benefit analysis. More often, a decision to "do something" is informed by cost-effectiveness studies. Interestingly enough, even these cost-effectiveness studies have played a relatively minor role in the level of the "something" finally agreed to and implemented. Ideally, the cost-benefit models can be used to inform the initiation and progress of the sequence of decisions and actions related to climate change policy —

i.e., the policy motivated research needs as well as the climate policy.

It is clear that building a single model capable of addressing all the nuances of this problem is not possible. Different approaches need to be adopted to address different questions. Any single model of the whole problem will by design have to treat many issues at a high level of abstraction. Much of the remaining discussions will focus on this special class of integrated assessment models. It is important to note that there are many other integrated assessments aimed at specific aspects of the climate change issue. For example, the GENESIS model being developed by Thompson *et al.* is an integrated assessment of the bio-geo-chemical cycle and climate. Other integrated assessment efforts are underway for combining the knowledge we have accumulated on ecosystem responses and socio-economic issues.

The *Real-politick* of the climate change issue demands that we learn about and simulate what is likely to happen to key groups. These impacts are both due to climate policies and climate change, i.e.:

- The folks who are encumbered by abatement initiatives. For example, as part of our integrated assessment effort we have examined the burden falling on the energy supply industry (14). In the case of energy producers, the impacts of climate policies are much larger than the impacts of climate change. In terms of political significance, the level and distributional character of the cost of abatement borne by households is just as important (15, 16). In general, whether looking at the energy sector or energy consumers, the cost of abatement policies is relatively small, and the number encumbered are large.
- The picture for the folks who are encumbered by impacts is completely different. Here, there are likely to be a small number of identifiable communities who are heavily impacted. They and their travails are likely to influence policy as much as, if not more than, the former.

Despite the effort expended, most of the integrated assessment models are developed at the level of a "representative citizen." Sometimes, this is a citizen of the U.S., at other times a citizen of the world (10). Unfortunately, there is a considerable chance that these studies will fail to produce the information policy makers use in their decision-making. Of all the integrated assessments in hand, only one considers the impacts from the perspective of different interest groups (17). It is only through cognizance of the perspectives of the various groups that the dynamics of the climate debate can be explored (18).

3. The Philosophy of Integrated Assessment at Carnegie Mellon

3.1. What is an Integrated Assessment?

At Carnegie Mellon, we have been using the term *Integrated Assessment* for over a dozen years to describe a very specific approach to policy motivated research. To begin with, it is appropriate to make sure we have a common understanding about the term integrated assessment. We believe integrated assessments to be a set of activities carried out in parallel to the normal course of research on complex issues. When many specialist investigators pour over different elements of the problem, someone needs to keep track of how the pieces of the puzzle are fitting together. In many cases, this putting together of the pieces of the puzzle may indicate what next to look for in the narrower disciplinary activities. So, the scope of an integrated assessment is broad. It is designed to explore the whole problem.

Continuing to use the analog of a puzzle, consider those devilish puzzles with viable patterns on both sides of the pieces. The completed pictures could be considered the "scientific objective" and the "policy objective." An identifia ble pattern on one side does not necessarily mean that the enigma of the picture on the other side of the puzzle has been solved. In our effort we are focusing on putting together the puzzle pieces which are needed to address the "policy objectives."4

In general, we develop a set of coordinated studies exploring various aspects of the problem. A central focus of these studies is the characterization and quantification of uncertainties. Whenever possible, we develop an all encompassing quantitative framework in which the uncertainties of all the various elements of the problem are captured, and propagated throughout the analysis. Such frameworks are an important aid to understanding the relative importance of the various components of the problem (identified through sensitivity analysis), and the importance of various components to the uncertainty in outcomes (identified through uncertainty analysis). Knowledge about these features of the problem permits more informed prioritization of policy motivated research. It is also a cornerstone for the design of policies that are resilient to uncertainties.

3.2. Accuracy vs. Precision

The traditional approach to model development has involved the endless pursuit of realism through detail. An approach which is based on the characterization and propagation of uncertainties often reveals large ambiguities in predicted outcomes. Under such circumstances, the addition of detail to models rarely serves a useful purpose.5 In practice, often the opposite is true and model users are lulled, by the precision of model structure and outputs, into a false sense of security in the accuracy of model predictions. An example of such potentially misleading precision can be found in both natural science and social science models. In natural science models of climate change, regional climate models offer precise forecasts in the absence of supporting foundation of science and data. An example from social science modeling can be found in the precision with which end-use energy is characterized for myriad industries in various models with nary attention to issues of technical change, economic restructuring and so on. We have found it more fruitful to keep the model simple, and iterate on the details only where needed to address policy relevant

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Policy motivated research and policy relevant research are easily distinguishable. All research is potentially policy relevant as new information can always influence our decisions. Policy motivated research seeks to develop understanding specific to policy makers decision needs. This implicitly determines the research agenda and time horizon for preliminary results from the research activity.

A useful purpose is served when the additional detail serves to fundamentally change the nature of the mapping from the input parameter space onto the output parameter space (e.g., a contractive mapping due to joint distribution of inputs, reducing the outcome uncertainties).

questions and permitted by available knowledge.

Finally a repetition of the motive for integrated assessments of technically complicated public policy questions. The aim for such integrated assessments is two-fold. The first goal is to better inform the design and implementation of public policies. The second goal is to provide tools for better management of resources devoted to addressing policy motivated issues.

3.3. Modeling and Uncertainty

With various theories and observations in hand, we build one of two types of models: i) models that do not purport to understand the underlying processes, and are only a mathematical mapping of inputs onto outputs; and, ii) models that are attempts at simulating the world processes and understanding how the inputs influence the outputs. Both types of models are subject to various uncertainties and errors. Observational problems can lead to three sources of error:

- Appropriate inputs and outputs may be poorly measured, or not measured at all. Developing a correct model under these circumstances is serendipitous. For example, fertility rates in Eastern Europe have declined at the same rate as stork populations. A model based on the role of storks' in child-bearing would have provided a good predictor.

- The observational data may be carefully collected, but the range of observations may not include their expected future range. This permits the development of a good model of past behaviour. However, the application of such a model to future predictions demands an assumption akin to Mach's Principle. The farther the departure of future input parameter values from past observations, the more likely that the assumption of model invariance is questionable.

- Finally, the observational data may be carefully collected, but these data and the model may be of different granularity. This too can lead to erroneous models. Many mathematical functions are not invariant under aggregation.

For example, we may have evidence that an exponential model is a powerful predictor of any individual's rate of time preference. It is tempting, but erroneous, to assume that an exponential function with appropriate parameter values is a similarly powerful predictor for a population.

3.3.1. Parameter, Model, and Algorithmic Uncertainty

In addition to model identification and specification errors, the modeling effort can suffer from at least three sources of uncertainty. There may be *parameter uncertainty*, where the empirical values needed as inputs to the model are not known with precision. Morgan and Henrion [19, p. 56] classify uncertainties in empirical quantities as arising from: statistical variation, subjective judgment, linguistic imprecision, variability, inherent randomness, disagreement, and approximation. There may be *model uncertainty*, where more than one model can be used to describe a system, and there is uncertainty as to which is more appropriate. Finally, there can be *computational uncertainty* where the algorithm or the computation engine adopted to solve the model introduce uncertainties. For example, the precision of computers is limited by the hardware and the numerical algorithms. It is important to remember that ubiquitous algorithms such as Newton-Raphson and Runge-Kutta only provide a numerical approximation to an analytic solution.

3.3.2. Value Uncertainty

Models are developed to answer questions. These questions pertain to things that we value, otherwise we would not expend the energy to investigate them. It is important to recognize that individuals may value different things (have different preference orderings) and that these preferences may change through time — often referred to as value uncertainty [19]. For example, there is often interest in the overall efficiency of a policy instrument in reduction of an environmental ill, as well as interest in their equity characteristics. When uncertainties are also considered, there are additional issues of: instrument choice; ancillary benefits and costs; ^Dnd level of environmental quality being sought.

Given a number of valued outcomes, it may be important to strike a balance among the different interests. Sometimes the tradeoffs are straightforward. For example, one may ask: at what additional cost will we be able to assure distributional equity of abatement costs according to some criteria? But the benefits of reducing an environmental ill are unlikely to be equally distributed under any scheme.6 Furthermore, how different people value the benefits is subject to variation. For example, one may be primarily concerned about the impact of CO_2 emissions on the occurrence of heat stress induced mortality, while another is interested in ecosystem impacts of elevated greenhouse gases and climate change. Thus, the notion of a single metric of impact, such as global warming potentials, is erroneous. Ideally, models should be able to calculate a variety of values so that tradeoffs between groups may be quantitatively investigated using the same model.

A final note about value aggregation and uncertainty concerns the goal of intergenerational equity. We do not know how preferences are formed and changed. Consequently, we do not know what the preferences of future generations are likely to be. Thus, while the notion of sustainable development is laudable, it is fundamentally impractical. It seems that our capacity to predict the time evolution of preferences has not progressed since the early twentieth century when Winston Churchill observed: "a young man who is not a socialist has no heart, and an old man who is not a capitalist has no brain."

4. Challenges Ahead

There are three different challenges on the horizon for integrated assessment studies of climate and global change. The first of these is related to the basic science

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Two reasons are offered for this assertion. First, that the exposure to the ills is unlikely to be uniform across the wide range of activities and behaviours that make up a population. Second, the dose: response ratio varies across individuals.

which provides the fundamental information used in developing Integrated Assessment (IA) frameworks. The second is in the methodologies for integrated assessment. The third is in learning what matters to decision-makers and designing integrated assessments so that they inform the decision-making process and are adopted by decision-makers in their activities.

4.1. Basic Scientific Challenges

In the modeling of socio-economic aspects of IAs we suffer a dearth of basic data outside democratic countries. For example, there are no incentives for collection of representative demographic data outside democratic societies. A spectacular example of this issue was found in Nigeria where in anticipation of democratic rule a new census was taken in 1991. This found 88.5 million Nigerians rather than the UN's estimate of 126 million[20]. Furthermore, the models we have developed to describe social dynamics have only been tested in the context of the democratic subset of the world. More generally, our knowledge of key dynamics of social systems is limited. These limitations include, but are not limited to:

- What brings about demographic transition, and how may population changes be predicted over the next century or more?
- What are the roots of technological innovation and diffusion?
- What has led to rapid industrialization in some countries and how have other countries failed to grow?
- How are preferences formed and do they evolve through time?
- Finally, a question common to all these issues. Can these be manipulated through specific initiatives?

In the realm of the natural systems we are faced with similar problems. The dynamics of the climate system continue to be far from well understood. The real difficulty arises from the dearth knowledge about the internal dynamics of this system. After all, greenhouse gases (other than water vapour and ozone) contribute about 5% of the global warming effect that permits ^Eife on earth. The remaining 95% is due to water vapour and ozone whose behaviour is internal to the climate system. The challenge in climate modeling is two fold: i) establishing some measure of confidence about the state of the climate system in the absence of anthropogenic influences, and ii) predicting the response of the 95% to perturbations in the 5%. The nascent nature of climate science is typified by a continuing stream of "surprise" findings and continuing disappointment in solving what were once thought to be tractable problems. For example:

- We are still at a loss as to how to model clouds [21].
- Balancing the "carbon-cycle" remains a challenge, made more difficult with recent evidence of a new reservoir of organic carbon in the oceans [22, 23].
- CFCs, once thought to be the most potent greenhouse gases, are now believed to have a negligible *net* warming effect [24].
- Fuel and biomass burning as well as biogenic sources lead to emission of greenhouse gases and aerosols. The former lead to long wave radiation being trapped in the atmosphere and "warming." The latter lead to reflection of short-wave radiation. Estimating the magnitude of this cooling effect continues to be a difficult challenge [25, 26].

- We have long known about the central role of ocean circulation in the global climate, but new evidence calls into question long held beliefs on the cause and effect in that relationship [27].
- And finally, there is paleoclimatic evidence of abrupt climate change and multiple stable states of climate (at least on a regional and possibly on the global scale) but there is insufficient data on what may have triggered these [28, 29].

In plant response studies we have learned about the importance of CO_2 fertilization effect on plants. However, even the first steps towards an understanding the ecological consequence of this matter are yet to be completed. A sensitivity analysis of a leading plant physiology model suggests the impact of changed CO_2 concentration to be greater than the impact of climate change (temperature, precipitation, and Photo synthetically Active Radiation) [30]. However, the most advanced global ecosystem modeling efforts continue to seek impacts on ecosystem distributions as a consequence of changes in temperature and precipitation [31]. This is an unsatisfactory situation when it is not even clear if our present characterization of ecosystems would persist.

4.2. Methodological Challenges

In the realm of methodological challenges there are three frontiers to push back. The first is the frontier of computational techniques for probability and uncertainty analysis in large integrated models. A typical challenge may involve a model such as ICAM-1 being used to explore the issue of research prioritization. The value of research will be dependent on the path of the discovery and concurrent path of investments in mitigation and adaptation activities. All of these factors are uncertain. This makes the optimization possibilities a large combinatorics problem and a computational nightmare. We need to develop efficient algorithms and robust heuristics for solving such problems.

The second problem is that of elicitation of knowledge from experts where the quantified models are unsatisfactory. This is unquestionably a potentially powerful tool. However, the successful practitioners exercise a black art and myriad basic and other problems have never been systematically investigated.

The third challenge is in representation of ignorance in models. This is one step beyond the consideration of uncertainties. To date, most of the major models Global 2100, Edmonds Reilly, CETA, and DICE have been run with stochastic sampling of their input parameters. However, there are only two climate IA models that have considered uncertainties in their design (PAGE and ICAM-1). Furthermore, strict Bayesian theory does not permit the definition of ignorance about a parameter. Some mechanisms exist for getting around the definition of a parameter about which one may be partially ignorant. We need to capture both uncertainties and ignorance in IA models. We especially need to capture ignorance where we have developed well behaved models of processes (over a limited range of observations) and suspect non-linearities, discontinuities, or bifurcations just around the corner.

4.3. The Challenge of Meeting Policy Maker Needs

Two issues need to be considered before integrated assessments can be made more useful to policy decision-makers. The first is to recognize that climate change is one of many possible issues decision-makers must grapple with. The second is that policy decision-makers do not seem to have made their decisions on the basis of cost-effectiveness or cost-benefit analyses in the past. Past evidence suggests that absolute costs and their distribution do matter. Who the beneficiaries are also matters. Finally, policy responses are often triggered by extreme events and rarely by secular trends in key parameters.

These observations suggest that model predictions need to be presented alongside measures of other global change and their impacts. This will help decision-makers calibrate their level of effort and reactions to climate change issues. In addition, integrated assessments need to predict distributional characteristics of costs and benefits. Finally, non-linearities and bifurcations need to be incorporated into the assessments. This is a tall order, but aiming to be valuable to the point of being indispensable is a lofty goal

5. Conclusion

In the preceding discussions an overview of the history and philosophy of integrated assessment has been presented. A number of conclusions can be drawn:

- Support for integrated assessments of climate change has already materialized in Europe in such projects as IMAGE, ESCAPE, and PAGE. Support for similar North American integrated assessment efforts is promised for 1995.

- More satisfactory and representative of the dynamics of social systems, ecological systems, and natural systems are needed before integrated assessments can be made more realistic. In addition, non-linearities, bifurcations, and ignorance about systems need to be incorporated into integrated assessment frameworks.

- We do not know how far integrated assessments are from providing the information decision-makers use. There is a need to more carefully examine the factors that shape policy-maker decisions. While this is the case, success of this powerful tool in the policy arena will be a matter of chance.

So the agenda is set for the various parties. The disciplinary scientists need to develop better models of the dynamics of processes they study; integrated assessment teams need to study the decision-making of policy-makers; and, policy-makers need to decide if integrated assessment is a useful tool that they would like to endorse and use more widely.

Table 1. A Taxonomy of Integrated Assessment Models

Model Name	Opt /Sim	Spatial Character	Temporal Character	Decision Variables	Comments
Cost Effectiveness Framing					
DGEM	S	U.S. with a ROW sector	1985-2050/^F1 yr steps	abatement	Inter-temporal general equilibrium model of economy with 35 production sectors, 5 energy supply sectors, & 672 households [1-3].
Edmonds Reilly Barns	S	9 world regions	1975-2095/ 15 yr steps	abatement	Regional energy economies that trade fossil fuels [4, 5]
Gemini	S	U.S.	1990-2030/ 5 yr steps	abatement	Inter-temporal general equilibrium of energy markets with 19 economic activity sectors.
Global 2100	O	5 world regions	1990-2100/ 10 yr steps	abatement	Five regional energy economies with inter-regional trade in oil [6].
Markal	O	U.S.	1990-2030/ 5 yr steps	abatement	LP model, rich in end-use and supply technologies
OECD - Green	S	8 world regions	1985-2020/ 5yr steps	abatement	Inter-temporal general equilibrium with 8 production sectors, 4 consumption categories.
Cost - Impact Framing					
Hammitt et al.	O	Global and 2 region models	2 periods with 10 year time interval	abatement &tempera-ture change	A two stage decision model with resolution of uncertainty at second decision point [7].
IMAGE	S	Impacts for The Nether-lands	1900-2100/ 0.5 yr steps	abatement & physical impacts	Emissions from Edmonds Reilly, followed by biogeochemistry, climate, sea level and impact modules [8]

MBIS	S	Mackenzie basin, Canada	1970-2050/ 10 yr steps	abatement & impacts	Detailed regional impacts market and non-market impacts estimated
Cost - Benefit Framing					
CETA	O	Global/ 2 region	2200/ 10 yr steps	abatement	Costs and precursors based on the Global 2100 model. Benefits based on DICE
DICE	O	Global	1965-2105/ 10 yr steps	abatement	Full integration of economic activities and impacts of climate change [9, 10].
ICAM-1	S	Global/ 2 region	1975-2100/ 25 yr steps	abatement, adaptation, geo-eng.	Probabilistic formulation, integration of economy and damages, market and non-market damages [11].
PAGE	S	Global/ 2 region	1990-2100/ 5-25 yr steps	abatement, adaptation.	Probabilistic, Multi-attribute Utility functions to display subjectivity [12].

Source: H. Dowlatabadi. "Integrated Assessment of Climate Change: an incomplete overview." in *International Workshop on Integrative Assessment of Mitigation, Impacts, and Adaptation to Climate Change*. 1993, 13-15 October, IIASA, Laxenburg, Austria.

References

1. D. W. Jorgenson and P. J. Wilcoxen, "Intertemporal General Equilibrium Modeling of U.S. Environmental Regulations," *Journal of Policy Modeling*, 1990.
2. D. W. Jorgenson and P. J. Wilcoxen. "The Cost of Controlling U.S. Carbon Dioxide Emissions." in *Workshop on economic/ energy/ environmental modeling for climate policy analysis*. 1990. Washington, DC:
3. D. W. Jorgenson, D. T. Slesnick and W. Peter J., "Carbon taxes and economic welfare," Harvard University, 1992.
4. J. A. Edmonds and J. M. Reilly, *Global Energy: Assessing the Future*. 1985, New York, Oxford: Oxford University Press.
5. J. M. Reilly, J. A. Edmonds, K. H. Gardner and A. L. Brenkert, "Uncertainty Analysis of the IEA/ORAU CO2 Emissions Model," *The Energy Journal*, 1987. **8**(3): p. 1-29.
6. A. S. Manne and R. G. Richels, *Buying Greenhouse Insurance - the Economic Costs of CO2 Emission Limits*. 1992, Boston, MA: MIT Press.
7. J. K. Hammitt, R. J. Lempert and M. E. Schlesinger, "A Sequential-Decision Strategy for Abating Climate Change," *Nature*, 1992. **357**(6376): p. 315-318.
8. J. Rotmans, *IMAGE: An Integrated Model to Assess the Greenhouse Effect*. 1990, Dorcrecht / Boston / London: Kluwer Academic Publishers. 289.
9. W. D. Nordhaus, "The "DICE" Model: Background and Structure of a Dynamic Integrated Climate Economy," Yale University, 1992.
10. W. D. Nordhaus, "An Optimal Transition Path for Controlling Greenhouse Gases," *Science*, 1992. **258**(5086): p. 1315-1319.
11. H. Dowlatabadi and G. Morgan, "A Model Framework for Integrated Studies of the Climate Problem," *Energy Policy*, 1993. **21**(3): p. 209-221.
12. C. W. Hope, J. Anderson and P. Wenman, "Policy Analysis of the Greenhouse Effect: an application of the PAGE model.," *Energy Policy*, 1993. **21**(3): p. in press.
13. H. Dowlatabadi. "Integrated Assessment of Climate Change: an incomplete overview." in *International Workshop on Integrative Assessment of Mitigation, Impacts, and Adaptation to Climate Change*. 1993. !3-15 October, IIASA, Laxenburg, Austria:
14. H. Dowlatabadi, R. Hahn, R. Kopp, K. Palmer and D. DeWitt, "How Reliably Can Climate Change Impacts on Electric Utilities Be Assessed?," *Utility Policy*, 1993. **3**(July): p. 261-268.
15. D. E. DeWitt, H. Dowlatabadi and R. J. Kopp, "Who bears the burden of energy taxes?," QE91-12, Resources for the Future, 1991.
16. F. T. Tschang, H. Dowlatabadi and R. Kopp, "A Regional Economic Model of the Energy Tax Burden on the Residential Sector," H.J. Heinz III School of Public Policy and Management, 1993.
17. C. W. Hope, "A Model for Policy Analysis of the Greenhouse Effect," Research Report, 11/92, Judge Institute of Management Studies, Cambridge University, 1992.
18. L. B. Lave and H. Dowlatabadi, "Climate Change Policy: The Effects of Personal Beliefs and Scientific Uncertainty," *Environmental Science and Technology*, 1993. **27**(10): p. 1962-1972.

19. M. G. Morgan and M. Henrion, *Uncertainty: A Guide to Dealing With Uncertainty in Quantitative Risk and Policy Analysis*. 1990, New York: Cambridge University Press.
20. Central Intelligence Agency, *World Factbook 1992*. 1992, Washington D.C.: U.S. Government Printing Office.
21. R. D. Cess, *et. al.*, "Intercomparison and Interpretation of Climate Feedback Processes in 19 Atmospheric General-Circulation Models," *J Geophys Res-Atmos*, 1990. **78**(D10): p. 16601-16615.
22. R. Benner, J. D. Pakulski, M. McCarthy, J. I. Hedges and P. G. Hatcher, "Bulk Chemical Characteristics of Dissolved Organic-Matter in the Ocean," *Science*, 1992. **255**(5051): p. 1561-1564.
23. J. R. Toggweiler, "Carbon-Cycle - Catalytic Conversions," *Nature*, 1992. **356**(6371): p. 665-666.
24. T. M. L. Wigley and S. C. B. Raper, "Implications for Climate and Sea-Level of Revised IPCC Emissions Scenarios," *Nature*, 1992. **357**(6376): p. 293-300.
25. Y. J. Kaufman, R. S. Fraser and R. L. Mahoney, "Fossil Fuel and biomass burning effect on climate--heating or cooling?," *Journal of Climate*, 1991. **4**: p. 578.
26. R. J. Charlson, S. E. Schwartz, J. M. Hales, R. D. Cess, J. A. C. jr, J. E. Hansen and D. J. Hofmann, "Climate Forcing by Anthropogenic Aerosols," *Science*, 1992. **255**(5043): p. 423-430.
27. R. Zahn, "Climate - Deep Ocean Circulation Puzzle," *Nature*, 1992. **356**(6372): p. 744-746.
28. W. Dansgaard, S. J. Johnson, H. B. Clausen, D. Dahl-Jensen, N. S. Gundestrup, C. U. Hammer, C. S. Hvidberg, J. P. Steffensen, A. E. Sveinbjörnsdottir, J. Jouzel and G. Bond, "Evidence for General Instability of Past Climate From a 250-kyr ice-core record," *Nature*, 1993. **364**(6434): p. 218-220.
29. T. Veum, E. Jansen, M. Arnold, I. Beyer and J. C. Duplessy, "Water Mass Exchange Between the North-Atlantic and the Norwegian Sea During the Past 28,000 Years," *Nature*, 1992. **356**(6372): p. 783-785.
30. E. Shevliakova, H. Dowlatabadi and M. J. Small. "Sensitivity and Uncertainty Analysis of an Individual Plant Model and Performance of its Reduced Form Versions: A Case Study of TREGRO." in *International Congress on Modeling and Simulation*. 1993. Nedlands, Western Australia:
31. T. M. Smith and H. H. Shugart, "The Transient-Response of Terrestrial Carbon Storage to a Perturbed Climate," *Nature*, 1993. **361**(6412): p. 523-526.

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8.2 Workshop Correspondence

November 2, 1993

Dear Participant:

I am pleased to invite you to participate in a workshop on the ***Impacts of Global Climate Change and Variability in the Great Lakes Basin***. The meeting is being cosponsored by NOAA/Great Lakes Environmental Research Laboratory, the Cooperative Institute for Limnology and Ecosystems Research (CILER) and the Great Lakes Commission. Last year, the Administrator of the National Oceanic and Atmospheric Administration charged me with developing the United States component of a binational Great Lakes global climate change study. The objective is to link the study with an ongoing initiative coordinated by Canada's Atmospheric Environment Service. The workshop will entail formal presentations and break-out discussion groups designed to:

- Assess the current status of global change research and impact assessment in the Great Lakes.
- Identify unmet needs in these areas.
- Develop a US Great Lakes Climate Change Research Plan to address these unmet needs and lay the foundation for Basin-wide adaptive strategies.

The workshop is scheduled to take place from **Noon on December 6 through Noon on December 8, 1993**. You, along with approximately 80 other participants, will provide excellent representation from numerous federal, state, and provincial agencies, and university/research institutions with interest and expertise in climate change. You will be asked to participate in a work group in which specific research objectives for that issue area will be formulated.

The workshop will be held at the **Radisson on the Lake Hotel.** For reservation and conference room rate information (mention "U of M CILER group"), please contact the hotel by November 13, 1993 at:

Radisson on the Lake
1275 Huron Street
Ypsilanti, MI 48197
(313) 487-2000
1-800-333-3333

Northwest Airlines has provided us with a special conference rate airfare for the workshop. To receive the conference rate, you must book your reservations through **Landmark Tours and Travel**, at **1-800-432-8636**. Please let Carole Fletcher or Jennifer Smith at (313) 764-2426 know by November 24th whether you will be able to participate in this important planning workshop. I look forward to working with you in this effort.

Sincerely,

Frank H. Quinn, Ph.D., P.E.
Head, Physical Sciences Division